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NETWORK CODING FOR COOPERATION IN WIRELESS NETWORKS

**BY
NÉSTOR JAVIER HERNÁNDEZ MARCANO**

DISSERTATION SUBMITTED 2016



AALBORG UNIVERSITY
DENMARK

Network Coding for Cooperation in Wireless Networks

Ph.D. Dissertation
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...a mi esposa y familiares que me apoyaron en estos años.

...to my wife and family members who supported me these years.

Abstract

Mobile users through wireless networks generate today a large demand in high-quality data services that is only expected to grow dramatically in the following years. This future demand will saturate the networks as we know them today. This becomes critical in scenarios with a very high density of users, e.g. sports stadiums, where the radio resources are insufficient to deliver a good Quality of Experience (QoE). Thus, exploiting techniques that better use the available resources by exploiting short-range communication alternatives, e.g. Wireless Fidelity (WiFi), Device to Device (D2D) in Long Term Evolution Advanced (LTE-A), to allow cooperation between users is at the crux of delivering the necessary QoE. In this scenario, mobile devices with any of the previous short-range communication technologies can cooperate by forming *mobile clouds*. These are clusters of devices exploiting a much faster and reliable communications link to share information. Network Coding (NC) has proven to be an effective solution in cooperative networks since it does not require to encode and decode on a hop-by-hop basis as state of the art erasure correcting codes require since: (i) it is possible to send recoded packets to a next hop with partial data, i.e. without having decoded and (ii) it is not required to receive each packet, but just enough coded packets instead.

In this thesis we focused on the design, analysis and simulation of cooperation techniques based on Random Linear Network Coding (RLNC) for wireless networks. First, we investigated the operational regimes where cooperative cellular networks perform better than broadcast cellular networks in terms of data rate and energy costs and also by considering different amount of cooperating devices. Two-fold gains or higher are achievable by our cooperative schemes by transmitting at least two times faster than with a broadcast scheme. We found that no more than six devices are required to be in each cloud to obtain these gains. Further, we reviewed code constructions to avoid the inherent RLNC trade-off for the total overhead between linear dependency or signalling when using a single field size. Our research permitted us to obtain codes that achieve less than 3% of total overhead in

our reviewed scenarios, compared to at least 10% when using RLNC. These works indicate when and how to cooperate between the devices to offload the network, while keeping a minimum overhead. Second, we evaluated two transmission policies and a Medium Access Control (MAC) mechanism to increase the throughput and reduce the energy consumption at the devices in a two-hop decentralized Wireless Local Area Network (WLAN) of one source, a number of relays and one destination. To achieve this, we developed a software framework that allows to analyze these policies in a simple way using the C++11 Kodo library and the ns-3 simulator. The software tool is publicly available to the research community as a major contribution. Our results show that between 50% and 75% gains are achievable by using the recoding feature from RLNC and an ideal device medium access probability. Our coding schemes and techniques address key challenges in state of the art cellular and wireless local area networks to enhance the throughput and reduce the energy consumption at the cellular Base Station (BS) and the mobile devices while keeping the total overhead to the bare minimum.

In the following years, the work in this area should focus on how to design and test practical implementations that show these gains, not only for current standards, but also for 5G technologies. Other aspects are to review how these metrics are affected the interference effect when orthogonal channels are not feasible with the cellular spectrum or review other metrics and code constructions to have a complete perspective of the solutions. In terms of the transmission policies, analytical works and simple derived heuristics from them to review optimal policies for mobile clouds with many devices to observe the achievable gains of these solutions.

Resumé

Mobile brugere via trådløse netværke genererer i dag en stor efterspørgsel i høj kvalitet, datatjenester, som kun forventes at vokse dramatisk i de følgende år. Denne fremtidige efterspørgsel vil mætte de netværke, som vi kender dem i dag. Dette bliver kritisk i scenarier med en meget høj koncentration af brugere, f.eks. sport stadions, hvor radioens ressourcer er utilstrækkelige til at levere en god QoE. Således, udnytter teknikker for bedre brug af de tilgængelige ressourcer ved at udnytte kortrækkende alternativer kommunikation, f.eks. WiFi, D2D i LTE-A, for at tillade et samarbejde mellem brugere er kernen i at levere den nødvendige QoE. I dette scenarie, kan mobile enheder med en hvilken som helst af de tidligere kortrækkende kommunikationsteknologier samarbejde ved at danne *mobile skyer*. Disse er klynge af enheder, der udnytter en meget hurtigere og pålidelig kommunikation link til at dele information. NC har vist sig at være en effektiv løsning i kooperative netværke, da det ikke kræver at kode og afkode på en hop-af-hop grundlag som state of the art sletning korrigere koder kræver siden: (i) det er muligt at sende omkodet pakke til en næste hop med delvise data, dvs. uden at have afkodet og (ii) er det ikke nødvendigt at modtage hver pakke, men bare nok kodede pakke i stedet.

I denne afhandling vi fokuseret på design, analyse og simulering af samarbejdsteknikker baseret på RLNC efter trådløse netværke. Først, undersøgte vi de operationelle regimer, hvor kooperative mobilnetværke udfører bedre end broadcast mobilnetværke i form af datahastigheden og energiomkostninger, og også ved at overveje forskellige mængder af samarbejdende enheder. To-fold gevinster eller højere er opnåelige ved vores kooperative ordninger ved at sende mindst to gange hurtigere end med en broadcast ordning. Vi fandt, at der ikke mere end seks enheder skal være i hver sky at få disse gevinster. Endvidere, har vi gennemgået kode konstruktioner for at undgå den iboende RLNC trade-off for den samlede overliggende mellem lineær afhængighed eller signalering ved brug af et enkelt felt størrelse. Vores forskning tilladt os at få koder, der opnår mindre end 3% af den samlede

overhead i vores revideret scenarier, sammenlignet med mindst 10% ved anvendelse RLNC. Disse værker viser, hvornår og hvordan man samarbejder mellem enhederne at losse netværket, og samtidig holde et minimum overliggende. For det andet, vi evaluerede to transmissions politikker og en MAC mekanisme til at øge throughput og reducere energiforbruget på enhederne i en to-hop decentraliseret WLAN af en kilde, en række relæer og én destination. For at opnå dette, har vi udviklet et framework der gør det muligt at analysere disse politikker på en enkel måde ved hjælp af C++11 Kodo bibliotek og ns-3 simulator. Den software værktøj er offentligt tilgængelig for forskersamfundet som et vigtigt bidrag. Vores resultater viser, at mellem 50% og 75% gevinster kan opnås ved hjælp af omkodning funktionen fra RLNC og en ideel enhed medium adgang sandsynlighed. Vores kodningssystemer og teknikker løse centrale udfordringer i state of the art cellulære og trådløs lokalnet at forbedre gennemløb og reducere energiforbruget på cellulære BS og de mobile enheder, samtidig med at den samlede overliggende til et absolut minimum.

I de følgende år, bør arbejdet på dette område fokus på, hvordan at designe og teste praktiske implementeringer, der viser disse gevinster, ikke kun for de nuværende standarder, men også for 5G teknologier. Andre aspekter er at gennemgå, hvordan disse målinger er påvirket interferens effekt, når ortogonale kanaler er ikke muligt med den cellulære spektrum eller gennemgå andre målinger og kode konstruktioner at have en komplet perspektiv af løsninger. Med hensyn transmissions politikker, analytiske værker og simple afledte heuristik fra dem at gennemgå optimale politikker til mobile skyer med mange enheder til at observere de opnåelige gevinster ved disse løsninger.

Thesis Details

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Ph.D. Student: Néstor Javier Hernández Marcano
Supervisors: Assoc. Prof. Daniel R. Lucani, Aalborg University
Dr. Janus Heide, Steinwurf ApS
Prof. Frank H.P. Fitzek, Technische Universität Dresden

The main body of this thesis consist of the following papers:

- [A] Néstor J. Hernández Marcano, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek, “On the Throughput and Energy Benefits of Network Coded Cooperation”, *2014 IEEE 3rd International Conference on Cloud Networking (IEEE Cloudnet)*, pp. 138–142, 2014. DOI: 10.1109/CloudNet.2014.6968982
- [B] Néstor J. Hernández Marcano, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek, “Throughput, Energy and Overhead of Multicast Device-to-Device Communications with Network Coded Cooperation”, *Wiley Transactions on Emerging Telecommunications Technologies (former European Transactions on Telecommunications)*. *Special Issue: Emerging Topics in Device to Device Communications as Enabling Technology for 5G Systems*, pp. 1–17, 2016. DOI: 10.1002/ett.3011
- [C] Néstor J. Hernández Marcano, Péter Vingelmann, Morten V. Pedersen, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek, “Getting Kodo: Network Coding for the ns-3 Simulator”, *ACM The Workshop in ns-3 (WNS3)*, pp. 101–107, 2016. DOI: 10.1145/2915371.2915389
- [D] Néstor J. Hernández Marcano, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek, “On Transmission Policies for Multihop Device-to-Device Communications with Network Coded Cooperation”, *IEEE 22th International Conference on European Wireless*, pp. 350–354, 2016.

In addition to the main papers, the following publications have also been made:

- #[1] Néstor J. Hernández Marcano, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek, "On the Overhead of Telescopic Codes in Network Coded Cooperation", *IEEE 3rd International Conference on Cloud Networking (IEEE Cloudnet)*, pp. 1–6, 2015. DOI: 10.1109/VTCFall.2015.7391046
- #[2] Néstor J. Hernández Marcano, Jeppe Pihl, Janus Heide, Jeppe Krigslund, Péter Vingelmann, Morten V. Pedersen, Daniel E. Lucani, Frank H.P. Fitzek, "Wurf.it: A Network Coding Reliable Multicast Streaming Solution - NS-3 Simulations and Implementation", *ACM The Workshop in ns-3: Posters, Demos and Short-Talks Session (WNS3)*, Available online at the ns-3 website: <https://www.nsnam.org/workshops/wns3-2016/posters/hernandez-demo-paper.pdf>, 2016.
- #[3] Néstor J. Hernández Marcano, Chres W. Sørensen, Juan A. Cabrera Guerrero, Simon Wunderlich, Daniel E. Lucani, Frank H.P. Fitzek, "On Goodput and Energy Measurements of Network Coding Schemes in the Raspberry Pi" *MDPI, Journal of Electronics. Special Issue for the Raspberry Pi (Indexed by Elsevier Scopus and Thomson-Reuters ESCI Web of Science)*, 5(4), 66, pp. 1-27, 2016. DOI: 10.3390/electronics5040066
- #[4] Chres W. Sørensen, Néstor J. Hernández Marcano, Juan A. Cabrera Guerrero, Simon Wunderlich, Daniel E. Lucani, Frank H.P. Fitzek, "Easy as Pi: A Network Coding Raspberry Pi Testbed" *MDPI, Journal of Electronics. Special Issue for the Raspberry Pi (Indexed by Elsevier Scopus and Thomson-Reuters ESCI Web of Science)*, 5(4), 67, pp. 1-25, 2016. DOI: 10.3390/electronics5040067
- #[5] Néstor J. Hernández Marcano, Wei Lu, Ricardo Bassoli, Marco Di Renzo, Daniel E. Lucani "A Stochastic Geometry Analysis of Broadcast Cellular Networks with Random Linear Network Coding" *In preparation*.

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Preface

This PhD thesis presents a collection of papers which consist on the research topics that were investigated throughout the three years of my PhD studies. The first half was as a member of the Antennas, Propagation and Radio Networking Group (APNet), Department of Electronic Systems, Aalborg University. The second half was as a member of the Wireless Communication Networks (WCN) section of the same department.

This thesis was prepared under the main supervision of Assoc. Prof. Daniel E. Lucani of the WCN section, Department of Electronic Systems at Aalborg University and co-supervisions of Dr. Janus Heide, CEO of Steinwurf ApS, Denmark; and Professor Frank H.P. Fitzek of the Technische Universität of Dresden, Germany. This work was mainly financed by the EU FP7 Marie Curie Initial Training Network CROSSFIRE (unCooRdinated netwOrk StrategieS for enhanced interFeRenCe, mobIlIity, radio Resource, and Energy saving management in LTE-Advanced networks) Project from the European Commission FP7 Framework (Grant No. EU - FP7 - CROSSFIRE - 317126).

It was also partially financed by the Green Mobile Cloud project granted by the Danish Council for Independent Research (Grant No. DFF - 0602-01372B). The thesis includes one journal article and three conference papers as its fundamental body. It also includes a complete list of all co-authored publications during the PhD studies.

Néstor J. Hernández Marcano

Aalborg University, November 4, 2016

Preface

Acknowledgments

All the experiences during the path of the PhD for the last three years have been incredible, very enriching and very enlightening both at a personal and technical level. These lines express my gratitude to all the people in this process.

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From my everyday life at work, I have to give special thanks to my peers at Steinwurf, Chocolate Cloud, Aalborg University, both the lab and the APNet and WCN sections specially the administrative staff for helping me to handle the thesis and the Crossfire Project for providing technical experience and a world class research network. From my life in Denmark, to all my friends and acquaintances that remind me that we only have one life to live. These lists are so long that I will need several pages. So to all of you, my deepest thanks!

Finally, some people think that doing a PhD is finding all the answers,

Acknowledgments

when is actually asking critical questions both technical and even personal. Therefore, I want to share with *you* two quotes that summarize my personal feelings of the PhD, since they represent what I think are the purpose of research and the persons that join us in the path of life.

V.V.V.V. - **Vi veri vniversum vivus vici:**

“By the power of truth, I, while living, have conquered the universe”

—‘V’ from V for Vendetta quoting the Faust

“Go alone and you will go fast, go together and you will get far”

—Ancient Proverb (Variant)

Néstor J. Hernández Marcano

Aalborg University, November 4, 2016

Part I

Introduction

Introduction

1 Background

Data demand is predicted to growth by a factor of 10 in 2020 from today's values by major network providers [1–4]. The use of cellular networks for data consumption has become widespread due in part to the massive increase in mobile applications and services for content delivery, e.g. Netflix, YouTube; social networking, e.g. Facebook, Twitter, Snapchat, Instagram; and cloud computing and storage, e.g. Dropbox, OneDrive, Amazon S3, Amazon EC2. Further, content delivery networks are expected to carry three-fourths of all the Internet video traffic by the end of 2020 [1]. Streaming applications that are based in multicast where a transmitter needs to serve tens, hundreds or even thousands of receivers are drawing large attention in mobile networks such as LTE-A or WLAN networks such as WiFi. Use cases of video streaming in highly-crowded scenarios, e.g. sports stadiums, airports, service-waiting areas or museums, are attractive but also challenging to the content providers. Serving a large amount of users with unicast schemes drain the network resources since each user needs a dedicated channel. Instead, it would be preferable a scheme where users are served in a broadcast fashion by synchronizing to it. These types of scenarios pose tight requirements to ensure a satisfactoring QoE for all the users. First, video services require high throughput and low delay to avoid stalling events in the end-user device. Second, to cope with the users data load, a high-capacity access network is required to accomodate all the users. Third, an efficient transmission schemes are required to serve them as quick as possible. To address these requirements, service providers should utilize 4G high-capacity mobile networks or WiFi networks using a broadcast scheme to serve all the users.

For the network operator, techniques that can offload the service infrastructure in a multicast network to cope with such data load, are needed in order to satisfy the overall demand and reduce the energy consumption at the BS. Further, given that all end-users experience different channel condi-

tions in such scenario, there might exist users with a degraded connection to a BS that increase the delay and reduce the throughput. Instead, a better connectivity might be provided by other users either within the cellular spectrum or through a WiFi network. However, the management of mobile devices without good cellular coverage but with access to this local network can potentially be decentralized.

For the mobile user, device internal energy consumption has become a limiting factor in terms of battery life due to data transmissions. Without a transmission scheme properly designed for reduced delay and high throughput, energy consumed by data transmissions can drain the mobile device battery reducing the time that a device request a service. Besides data transmissions, mobile devices perform much more internal tasks than older devices from ten years ago and since energy has become critical for the users [5–7].

Therefore, mobile network designers need to consider mechanisms and techniques that aim for high throughput and low energy consumption both at the station and the end user devices and that are able to provide data offloading from current network infrastructures. An effective solution to this problem is to consider cooperation between the devices. This approach exploits short-range communication protocols between the mobile devices, e.g. WiFi, Bluetooth and more recently D2D in LTE-A within the cellular spectrum, to offload the network and improve the mentioned metrics.

1.1 Cooperative Wireless Networks

The concept of cooperation in wireless networks has been investigated before [8–10]. The main goal is to diminish the amount of communications resources (data rate, energy or even storage and computational power) to convey an information of common interest from a transmitter to a set of interconnected receivers in a multicast fashion. Devices connected in this way form a *mobile cloud* [10]. In these prior works, cooperation through WiFi or Bluetooth for the short-range was always preferable than broadcast in former 2.5G and 3G cellular networks since the data rates for the short-range were much higher than the cellular ones. However, the appearance of D2D in LTE-A calls this assumption into question since both cellular and short range data rates are comparable. Therefore, it is required to understand when does cooperation becomes a better choice than broadcast for these scenarios in terms of rate and energy costs. In Fig. 1, it can be observed a comparison example of no cooperation and cooperation in a multicast wireless network.

Without cooperation, a purple content is sent to two mobile devices in a broadcast fashion. This requires a large downloading time and energy ex-

1. Background

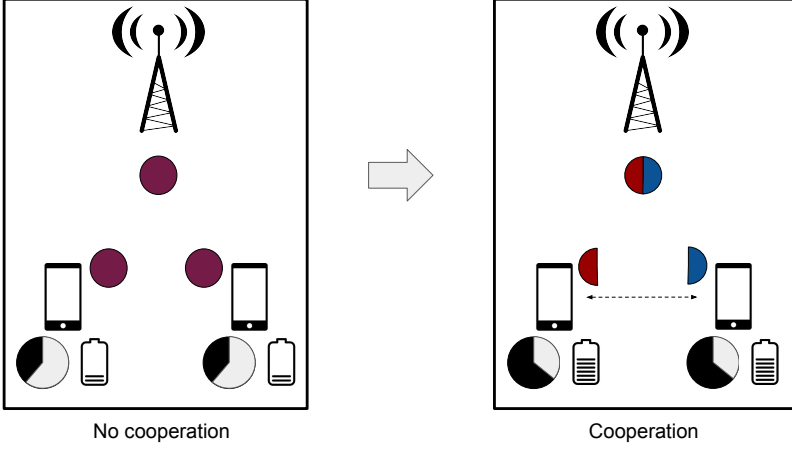


Fig. 1: Cooperation in Wireless Networks.

penditure to send two copies of the content (one to each device) and ensure both devices are satisfied. When cooperation is considered, the content now is split into smaller blue and red pieces where each of them is sent rapidly to each device. Thus, half the cellular resources are used in this example. Then, the devices exploit short-range communications (dashed line) by exchanging their missing pieces. The key underlying idea is for the devices share their missing information through a faster, short-distance and reliable link where data rate and energy costs are expected to be higher than in the cellular network. This increases the total throughput and reduces the overall energy consumption since the time and energy to distribute the information is reduced. From an operator perspective, the information *as a whole* is quickly disseminated into the receivers helping the BS to offload data. At the end, the goal of reducing the use communication resources at the BS is achieved. In this way, mobile clouds allow to improve the overall network performance and user experience.

1.2 Device to Device Communications in Mobile Networks

One of the key aspects to achieve the gains proposed by the cooperative approach is the short-range technology to be considered and its parameters to guarantee a fast and reliable link. Besides WLAN technologies like WiFi, there has been a large interest in D2D communications integrated into LTE-A [11–14]. This permits the devices to share data without going through

the BS network which keeps the idea of data offloading. The work in [12] proposes a classification of D2D communications. First, according to its spectrum use, the communications could be in the cellular network (inband) or outside in a local network (outband). Second, for inband D2D the communications could take place in the spectrum of other mobile users (underlay) or another dedicated only to D2D (overlay). Second, for outband D2D, the coordination between cellular and local network radio interfaces is either controlled by the cellular BS (controlled) or the users themselves (autonomous). For network assisted or inband D2D, authors in [15] review the key challenges to enable D2D services. Device discovery, communications resource allocation and coordination for these type of communications are handled by the cellular network. Furthermore, D2D based Proximity Services (ProSe) have been included in [16] to use them in LTE-A networks for an improved QoE.

1.3 Erasure Correcting Codes for Multicast Networks

Another aspect that is relevant for cooperation gains in multicast scenarios is channel coding. The dynamics of the wireless medium, propagation conditions, noise and interference may degrade the received Signal-to-Interference-plus-Noise Ratio (SINR) thus making reception unfeasible for some period of time. In the case of packet networks, this leads to *erasure* channels where packets are either correctly received or lost. Therefore, to protect against packet erasures, some redundancy is added with an erasure correcting code. They are relevant to make multicast applications reliable since error protection mechanisms with feedback based on retransmissions, e.g. Automatic Repeat-reQuest (ARQ), are very costly in the case of multiple users. For example, if we consider a multicast scenario with a 1% packet loss rate for all the links when transmitting 100 packets to 1000 users, this means that with high probability all data packets would need to be sent again at least once more time plus the required Acknowledgment (ACK) packets. However, adding 10% or less redundancy might be sufficient to complete the transmission of missing packets to all receivers. Thus, ARQ based schemes with feedback control through ACK packets are not possible for a large number of devices.

Different erasure correcting codes might be used for reliable multicast applications. In the literature, we can find linear block codes such as Reed Solomon (RS) [17] or Low Density Parity Check (LDPC) [18]. These codes fix the amount of redundancy to be generated for error correction from the original data through a *code rate* which depends on the packet loss rate. Still, if the packet loss rate varies they may generate too much redundancy or

1. Background

even not be able to correct erasures. More recently, Luby Transform (LT) codes [19] and Raptor codes [20] are more adaptable to the channel conditions than block codes since they always generate redundancy regardless of the channel conditions, thus being called *rateless* codes. These latter type of codes are characterized by being: (i) able to generate a large number of coded symbols due to the rateless property, (ii) close-to-optimal, requiring a slightly higher amount of encoded symbols than the original set to decode, and (iii) able to decode with a subset of coded symbols as long as there are no interdependencies in it. These erasure correction properties among others have led to consider Raptor codes its standardization in multicast LTE-A networks through the Evolved Multimedia Broadcast Multicast Services (eMBMS) protocol [21]. Later, RaptorQ codes from Qualcomm [22] were proposed as an extension of Raptor codes.

Although these coding techniques are useful for multicast networks, they pose two major restrictions to apply them in a cooperative approach. First, this type of coding is made on a *end-to-end* basis, meaning that for each hop encoding and decoding is required to be made before sending coded packets to the next hop. The required code processing for each hop increases the delay and energy consumption due to computational costs [23]. Second, as a consequence of the previous, these codes are not composable. Although there has been constructions composable rateless codes, e.g. distributed LT codes [24], its operational conditions are very restrictive and thus, impractical in general. This implies there are no practical forms to create new coded packets from packets that have been coded previously without decoding in the case of rateless codes. Because of these limitations state of the art rateless codes are not ideal erasure correcting codes for cooperative wireless networks with D2D due to the inherent processing in multi-hop.

1.4 Network Coding for Multicast Networks

Introduced by Alshwede et al. [25], NC appeared as an effective technology to remove the limitations presented previously. In this work, the authors presented a new paradigm shift for conveying information in communication networks. Instead of treating the packets as atomic, unmodifiable units at the intermediates node in a network, they are regarded as algebraic elements in a Galois Field (GF) that can be operated on to create new coded packets. RLNC [26] was introduced by Ho et al. In this scheme, coded packets are algebraic linear combinations of original set of packets from a single data flow. This type of coding can be made across any node in the network. Further, RLNC is proven to achieve the multicast capacity from a flow perspective with very high probability [26, 27]. In this way, instead of typically encoding

and decoding on a hop-by-hop basis, as it would happen with other erasure codes, coding is performed on a *network* basis. Relaying nodes can recode packets to reduce delay and still take advantage of the data representation for the next hop. Also, recoding can occur with partial information, meaning that as packets are received from a previous hop without decoding. In this sense, RLNC appears as the only coding technique that overcomes the restrictions mentioned earlier in Section 1.3.

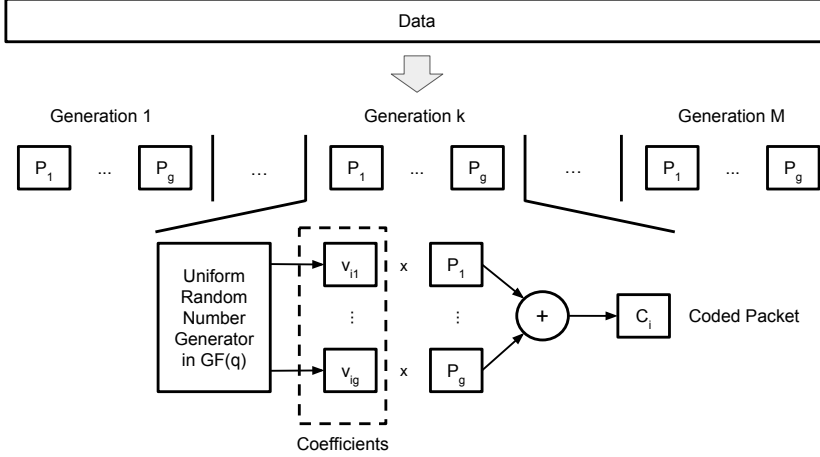


Fig. 2: RLNC encoding process.

As seen in Fig. 2, in RLNC the information to be transmitted is split into packets which are grouped into sets called *generations* [28]. Each generation $k = 1, \dots, M$ consists of g original packets P_i , $i = 1, \dots, g$ used to create new coded packets as with any Forward Error Correction (FEC) technique from Section 1.3. For each generation, each coded packet generated is a linear combination of all the original packets $C_i = \sum_{j=1}^g v_{ij} P_j$, $i \geq 1$. Here, v_{ij} is the coding coefficient that multiplies packet j in the process of creating packet i . The coefficients are picked uniformly at random from $GF(q)$ where q is the field size. All the operations are properly defined under the arithmetics of $GF(q)$.

After creating a coded packet, it is necessary to signal the coding coefficients utilized for encoding to the decoder. The signalling method that guarantees potential recoding without major caveats, is to append each coding coefficient used to create that coded packet as overhead. For each coded packet there is an overhead of $|v_i| = \sum_{j=1}^g \log_2(q) = g \times \log_2(q)$, [bits] $\forall i$. To get the original packets, a decoder only needs to collect *any* set of g lin-

1. Background

early independent coded packets to create a $g \times g$ matrix with the coding coefficients and perform Gaussian elimination [29] to solve the linear equations made in the encoding process. Depending on the field size and even considering no packet losses, the amount of transmissions required to collect g linearly independent coded packets might vary. This is due to linear dependency which refers to the amount of linearly dependent coded packets that are generated during the transmission process. As more linearly independent coded packets are received during the transmission process, linearly dependent coded packets are generated more frequently towards the end of the transmission.

Despite being a relatively recent technology, practical applications of RLNC started to appear a few years after its inception. The work of Chachulski et al. in 2007 considered Multipath Opportunistic Routing Engine (MORE) [30], the first protocol using RLNC which showed different achievable gains in real wireless mesh networks. Different areas with RLNC use cases can also be found in [29]. Also, RLNC has found applications in areas such as: Peer to Peer (P2P) networks [31], distributed storage [32] and network coding based Transmission Control Protocol (TCP) [33]. Moreover, standard software libraries have appeared such as Kodo [34], a network coding C++11 library whose purpose is to ease the development of protocols using RLNC.

1.5 Network Coding for Cooperative D2D Networks

For reliable multicast, various works have been made to quantify the gains of broadcast with RLNC against other transmission schemes in terms of erasure codes, feedback possibility and transmission policies. Among these, it can be mentioned: throughput and delay gains of reliable multicast with RLNC [35], time division duplexed channels [36, 37], (implementation on real devices [38] and protocols with resource allocation of multicast RLNC based networks [39–41]). Similar to fountain rateless codes, the key underlying idea is that RLNC creates indistinguishable coded packets helping many receivers to recover different lost packets at the same time. At the end, this capability helps all the end-users to obtain the required data much faster increasing the throughput.

Different from other erasure correcting codes, RLNC is well-suited for multicast cooperative networks due to its recoding capability. Using RLNC allows to create recoded packets *on-the-fly*, meaning as soon as previously encoded packets are received at a node [23, 42, 43]. RLNC does not incur in processing delays required by decoding and encoding new packets such as conventional erasure correcting codes as mentioned earlier. This feature has made RLNC an alternative code in cooperative networks. Studies that have

considered multicast cooperative mobile clouds with RLNC have been related to: cooperative mobile clouds for energy reduction [44], social mobile D2D clouds [45] and optimal transmission policies for broadcast and cooperation between unicast D2D pairs [46, 47]. Although very diverse, these studies have focused mostly in D2D pairs or standard RLNC solutions while omitting possible improvements both allowing the devices to multicast and considering alternate code constructions. Moreover, these studies assume that the D2D links are faster which could not be the case with new advances in mobile networks.

2 Thesis Outline

In this section, we define the observed challenges from the state of the art in the area and which are our proposals to solve them. Based on this, we define the thesis objectives to go beyond the state of the art. At the end, we describe the research lines to attain these goals. The particular contribution of each paper of the thesis and its related publications are detailed in Section 3.

2.1 Challenges in the State of the Art

Currently from the state of the art, different problems were identified from both prior work and observations during the thesis. These occur at different levels of the cooperation process when sending a content from the BS to the mobile devices. These problems pose specific technical challenges. The problems addressed in the thesis were: (i) which transmission schemes do the device use to cooperate, (ii) how many should cooperate, (iii) which are ideal codes to achieve a high throughput and low energy consumption at the devices and the BS and (iv) how should the devices be scheduled to transmit once the schemes are defined. Therefore, we describe the major challenges posed by these problems and how they were addressed during this research.

1. Cloud Sizes: From Unicast D2D Pairs to Multicast D2D Multi-Hop Clouds

The state of the start has considered the use of short-range communication technologies to establish unicast transmission between pair of devices to download a content and reduce the total completion time from a BS [46, 47]. To observe potential gains in these scenarios, we investigated the potential of multicasting to more devices inside the mobile cloud to cooperate in papers [A], #[1] (from the co-authored) and [B]. To understand the potential gains, Fig. 3 presents the benefits of increasing the amount of devices that cooperate to share a content. The figure considers a scenario similar to the presented in Fig. 1. It indicates the mean total number of transmissions required to decode a batch of g packets coded with RLNC in a multicast network of a BS and N devices vs. the number of devices cooperating inside each cluster (cloud size) N_u . Thus, there are $\lceil \frac{N}{N_u} \rceil$ clusters and $1 \leq N_u \leq N$. This figure presents the spectrum of cooperation since $N_u = 1$ represents the case of broadcast, i.e. no cooperation between neighboring devices; $N_u = N$ represents full cooperation of one cloud with all the devices and all other cases represent variable degrees of cooperation of various clouds with some devices.

For this reference scenario, it is assumed that all the packet erasures are independent and identically distributed. Also, all the devices present the same packet erasure probability ϵ for simplicity. It is also assumed that all devices have connectivity with the BS and are fully connected through a short-range orthogonal communications channel, e.g. D2D, WiFi network, etc. The packet erasures of the links inside the cloud are also independent and identically distributed with probability ϵ' . Also, we consider the case where $N \gg g$. After some transmissions have been made from the base station, the devices share locally coded (or recoded) packets in rounds with broadcast with RLNC in a coordinated fashion. An orthogonal channel is used to recover from the packet erasures when the BS transmitted. By reviewing the scaling laws of this metric in [35] and analyzing this scenario, some trends can be obtained.

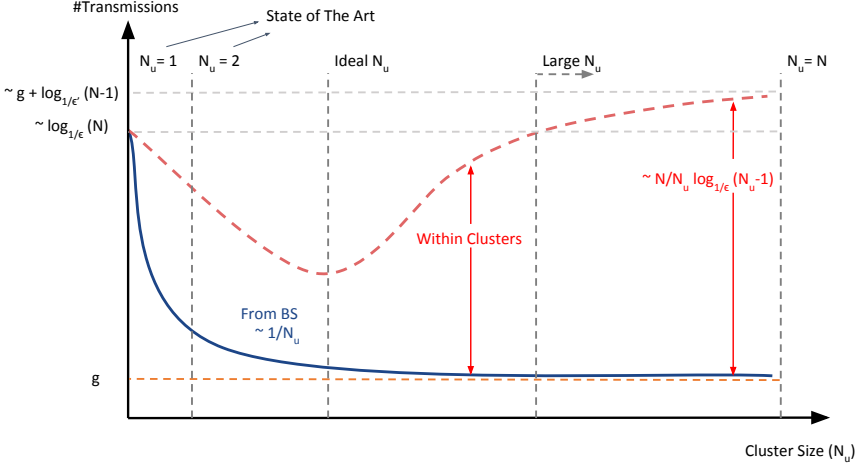


Fig. 3: Total number of transmissions trends vs. Cluster size.

First, the mean total number of transmissions of broadcast with RLNC of N devices, homogeneous packet erasure probability ϵ and $N \gg g$ scales as $\log_{\frac{1}{\epsilon}}(N)$ [35]. This is the value at $N_u = 1$. Second, the blue curve models the mean number of transmissions that the BS makes. As $N_u \rightarrow N$, the number of transmission from the BS approaches to the bare minimum g . This occurs because the probability of not receiving a packet in a cloud is ϵ^{N_u} , which vanishes rapidly for increasing N_u . Third, the red dashed curve stands for the total number of transmissions of the devices. This curve accounts for both the transmissions from the BS and inside each cloud. When the clouds are small, the amount of transmissions from the BS diminish more rapidly than the amount of transmissions inside each cloud. However, after

some amount of devices per cloud, adding more devices does not reduce the amount of transmissions from the BS significantly. Instead, this only increases the amount of transmissions within the clouds. As $N_u \rightarrow N$, the total number of transmissions of the devices approaches to the maximum possible, $g + \log_{\frac{1}{\epsilon}}(N - 1)$ since at least one device is transmitting at every round.

Currently, the state of the art considers using either $N_u = 1$ or $N_u = 2$ since it is not considered to multicast to many devices with RLNC. More important, from Fig. 3 it can be observed that an optimal cloud size exists to reduce the number of transmissions. This value also represents the operational point of highest throughput and lowest energy consumption vs. other designs with a different cloud size. Therefore, the regimes and conditions to achieve these values were investigated by looking when is cooperation better than broadcast in terms of the ratio of the data rates of the cellular links and between the D2D links. We also varied the amount of devices with connectivity to the cellular network inside a cloud.

2. RLNC Performance Parameters: Design Trade-Off

There has been different studies that addressed the impact of RLNC parameters in its performance, i.e. the generation size g and the field size q , in both theoretical and practical applications with mobile devices [36, 38, 48–51]. The generation size affects the algorithmic complexity of both encoding and decoding. The computational complexity of encoding RLNC packets scales as $\mathcal{O}(g)$, i.e. linear, since it involves g multiplications and $g - 1$ sums. For the decoding, Gaussian elimination is of cubic complexity $\mathcal{O}(g^3)$ in principle, given the inversion of a square matrix of size g . However, a structured Gaussian elimination implementation for RLNC can achieve $\mathcal{O}(g^2)$ for $g < 512$ as reported in [51]. Given that the field size effects are diverse, we summarize them in Table 1 which shows the effects of the field size for two principal regions: low and high field sizes. The criteria to separate them has been to consider a field size as high for values higher than 2^8 for reasons that will be explained below. The table also displays various metrics to evaluate the performance of the code.

As mentioned in Section 1.4, more linearly dependent coded packets are generated towards the end of the transmission process. Dependent packets are useless since they provide no new information to the decoder and are discarded. Once $g - 1$ independent coded packets have been received, the probability of generating a dependent coded packet is $\frac{1}{q}$ [36, 49, 50]. For the binary field, i.e. $GF(2)$, there is a 50% chance of generating useless packets. In the case of $GF(2^8)$, this chance reduces to less than 0.5% making it de-

Table 1: Field size effects in the code performance.

q	Linear Dependency	Signalling	Overhead Major Contributor	Field Complexity
$< 2^8$	High	Low	Linear Dependency	Low
$\geq 2^8$	Low	High	Signalling	High

preciable in practice. In terms of the generation size, the linear dependency effect can be observed on the average amount of transmissions for decoding. For $GF(2)$, $g + 1.6$ transmissions on average are required to decode the original set, whereas for $GF(2^8)$ this value can be approximated to g for practical purposes.

Signalling is interpreted as the amount of bits required to represent the coding coefficients. These bits are attached to each coded packet and for each original packet [48]. We referred to this value previously as $|v_i| = g \times \log_2(q)$ which grows linearly with g and logarithmically with q . For $GF(2)$, only 1 bit per packet is required to be included in each coded packet to signal the coding coefficients. However, for fields sizes of $q = 2^8 = 256$ or higher, one byte or more are necessary for each original packet to signal its coding coefficients. Therefore for high generation sizes, high fields could potentially make the amount of signalling much larger than the original packet size. Thus, overhead accounts for both effects of the linear dependency and coding coefficients signalling respect to useful data. In Table 1, it has been specified which is the effect that accounts for most of the total overhead in the specified region. For low fields, most of the overhead comes from linear dependency effect, but for higher field sizes the signalling from the coding coefficients becomes critical.

Finally, field complexity accounts for the computational cost and time required for the operations in GF arithmetics required to process the data. Besides algorithmic complexities, the field utilized to operate on the data affects the code performance in terms of time and energy spent on processing. The binary field poses a low computational burden on the device carrying the operations since modulo-2 operations are XOR/AND operations. However, increasing the field size requires to define and operate with new arithmetics which incur in higher processing times. Thus, a proper field size for mobile devices is important to ensure a satisfactoring code processing speeds [38, 51].

In terms of mobile applications, all of these aspects relate to the throughput and energy consumption. Ideally, parameter configurations that achieve: (i) low number of transmissions required to decode, (ii) low total overhead

2. Thesis Outline

and (iii) low field complexity are desirable. Such code performance metrics would lead to the goal of high throughput and low energy consumption at the mobile devices and the BS. However, as seen from the previous description, these objectives are conflictive posing a *trade-off* for using only RLNC in our scenario. Since most of the state of the art in this network coding area considers RLNC as its erasure correcting code, other code constructions that avoid the presented trade-off should be considered in order to achieve the previous goals.

3. Evaluation of Transmission Policies in Wireless Local Area Networks

In order to obtain rules to schedule transmitters in multicast scenarios with RLNC, the works in [46, 47, 52] have evaluated the cases of: (i) multicasting to D2D cooperative pairs and (ii) multicasting to a pair of nodes sharing a unidirectional unicast link in the presence of interferers. In these works, the theoretical problem of finding the ideal policy reduces to solving a Markovian Decision Process (MDP). However, obtaining the best policy poses a computational burden that is unfeasible in real networks, thus requiring the application of heuristics that are evaluated in self-defined numerical simulators or even implementations. Using these simulators to evaluate heuristics could potentially not be maintainable or reusable slowing the design process of the protocol developers. Moreover, these protocols assume that the devices have been assigned orthogonal communication resources. Nevertheless, in scenarios of this type, devices may access the medium in an uncontrolled manner thus requiring the evaluation of a decentralized access method. Therefore, we considered a software framework developed in paper [C] for the ns-3 simulator [53] which is well tested, supported and maintained. The purpose is to have a standard simulation environment to evaluate simple heuristics as we made for two transmission policies of a network with various relays in paper [D] and for a reliable multicast demo in paper #[2].

2.2 Objectives

Based in the previous challenges, this thesis pushes the state of the art by using multicast D2D mobile clouds in cooperative wireless networks with RLNC and other network codes since current techniques focus mostly in D2D communications based in unicast pairs with either RLNC or non-composable rateless codes. Therefore, the objectives of this thesis are to:

1. Define the regions and conditions in terms of the energy, data rate costs but also code parameters, where cooperation with RLNC pro-

vides a better performance than broadcast with RLNC in terms of data throughput and energy consumption at the BS and the mobile devices.

2. Study the dominating regimes and ideal cloud sizes to observe if there exists ideal values for high system throughput and low energy consumption for multicast D2D cooperative clouds as described in Section 2.1.
3. Propose and study code constructions that overcome the RLNC trade-off and achieve the goals described from Section 2.1. In this sense, the objective is to find codes that permit to retain the low coding coefficients overhead from a low field size, but also the low number of transmissions overhead from high fields.
4. Study the effect of transmission policies under a WLAN scenario in an easy-to-deploy manner. In this case, medium access mechanisms to avoid interference should be considered. Also, the use of standard simulation tools that are reusable for the research community and well maintained is desired.

2.3 Research Lines

To achieve the previous objectives and based on the concepts of multicast D2D communications with network coding in cooperative wireless networks, we followed the research path shown in Fig. 4. The figure shows the evolution from current multicast networks to our proposal. Existing 4G mobile networks offer to work with a broadcast scheme, e.g. LTE-A eMBMS to address streaming services. As mentioned earlier, this scheme does not allow cooperation and may utilize either rateless codes or RLNC for FEC at the application layer. Thus, the current state of the state proposals have evaluated cooperation techniques based in D2D pairs. However, as seen from Section 2.1, using more devices to cooperate has significant advantages. Moreover, as described in Sections 1.3 and 1.4, only RLNC can be applied to avoid the caveats from end-to-end rateless codes. Still, as mentioned in Section 1.4, RLNC codes present a trade-off between linear dependency overhead, signalling overhead and field complexity.

Our proposal focuses on the rightmost diagram of Fig. 4 where we have indicated the thesis papers that review the objectives mentioned in Section 2.2. We divided the research in two major lines to achieve the objectives previously stated which we describe below. The first line goal was to obtain network codes and operational regimes for cooperation in inband underlay D2D multicast cellular networks to enhance the throughput, reduce the energy consumption from the BS and the mobile devices, but also minimize the

2. Thesis Outline

total overhead from RLNC. The second line goal was to investigate transmission policies for mobile devices in a decentralized multi-hop WLAN to also improve the previously mentioned metrics in this type of networks utilizing simulation frameworks that could be reproducible and are well accepted, tested and maintained.

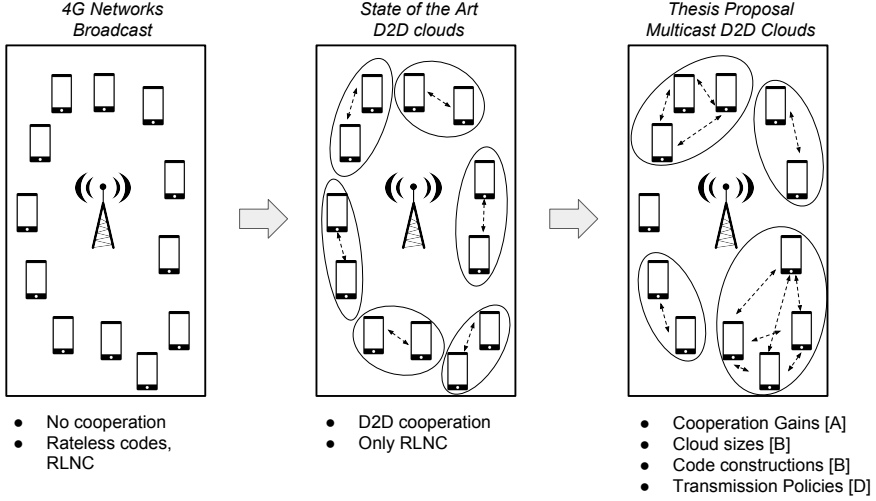


Fig. 4: State of the Art and Thesis Proposal.

1. Network Code Constructions and Regimes in Multicast Cooperative D2D Cellular Networks

Given the increase of data rates in cellular networks such as LTE-A, we first addressed the question of when is it reasonable for a set of devices to cooperate when downloading a multicast content in a cellular network. The underlying reason is that there has been improvements on the cellular data rates that had approached them to the order of local area network data rates. Thus, in paper [A], we investigated which are the regions where cooperation with RLNC achieves a better performance than broadcast with RLNC in terms of the data rate and energy costs for each transmission, to address objective 1 of the thesis proposal in Fig. 4. To do so, we reviewed two RLNC based schemes: broadcast and full (single cloud) cooperation with different parameters since we wanted to observe the spectrum of cooperation. We considered a variable of number devices with cellular connectivity which we referred as *heads* since they transmit to the devices without connectivity, i.e. the *non-heads*. For the latter scheme, multicast D2D communications take place within the cellular spectrum in a round-robin coordinated manner for the devices to distribute

their content. We considered the problem of reliably transmitting a batch of g packets using RLNC with a field size q in a time-slotted system. We considered independent heterogeneous packet erasure rates on the links from the source to the receivers to derive the expressions, but evaluated them to the same value for simplicity. For the local links, we considered bidirectional symmetric channels with the same packet erasure rate. We modeled both the throughput and the energy consumption as function of the number of transmissions required to decode for both schemes and found its analytical distributions. Later, we assigned a cost to each transmission according to values from the state of the art. We defined the cooperation gains as the regions where the cooperation scheme incurs in less transmissions than the broadcast scheme and calculated them with numerical simulations. From this work, we observed that codes with standard generation size and high field size, provided a reduced amount of transmissions translating into at least two fold gains for the throughput and energy consumption by just transmitting with data rates two times higher in the local area network than in the cellular network. However, in this work we did not include the effect of the signalling due to the coding coefficients which will reduce the gains mentioned metrics impacting in the choice of a coding scheme but at the expense of including overhead due to the coding coefficients used in RLNC.

In paper [B], we extended the analytical framework from paper [A] in various aspects. First, we include all the cooperation spectrum mentioned in Section 2.1 by considering various mobile clouds with a variable number of heads per cloud to address objective 2 from the proposal diagram of Fig. 4. Second, we refined our model by defining our network as an inband underlay D2D mobile network. Thus, we considered that any interference is managed in these scenarios by an arbitrary resource allocator from the cellular network. Hence, the interference is prevented under pre-defined network planning. We also consider how to make our system reliable in a practical manner by including simple feedback rules. To overcome the RLNC trade-off, we evaluated code constructions to optimize and reduce the total overhead from both redundant transmissions and coding coefficients to address objective 3 from our proposal in Fig. 4. We considered the employment of Telescopic Codes (TC) [54] which are a very recent advances on the state of the art and had not been considered for these scenarios. We extended further our analytical framework to include these codes and observed that RLNC is a special case in our framework. Finally, we analyzed the possible D2D cooperative cloud (cluster) sizes to observe the operational regimes first with heterogeneous sizes and finally with homogeneous sizes. We found that a homogenous cloud size provides the best possible scenario to improve our metrics. Our results achieve a total overhead of less than 3% with respect to a 10% when using RLNC.

2. Transmission Policies in Wireless Local Area Networks

To evaluate transmission policies in a simple and reproducible fashion, we first made a software framework with the ns-3 simulator [55, 56] in paper [C]. The purpose of the framework was to enable network coding simulations with the Kodo library in standard open source simulators aimed for the research community. For this work, we reviewed the state of the art in terms of simulators aimed for network coding applications. We found that, although there were initiatives in this area, there was missing a proper simulation tool for the network coding area deployed in standard frameworks that is well supported, tested and maintained. Thus, we considered using the ns-3 simulator with Kodo as an external library that provides the network coding functionalities. We indicated how to do this procedure. To date, this source code is maintained with the most recent and stable version of ns-3. This software consists of a set of examples broadcast and multi-hop networks using network coding to transmit a batch of packets since these were our cases. Nevertheless, we indicate to any developer user how to make their own examples in [55]. For beginner users, we created a descriptive tutorial in [56], that shows how to run the examples and what do they simulate. The examples deploy a protocol stack over ns-3 using its implementation of the Open Systems Interconnect (OSI) layer protocols. We implemented a RLNC coding layer using Kodo above an User Datagram Protocol (UDP) socket layer. Our implementation uses the Kodo and ns-3 Application Programming Interface (API) through C++ classes that are helpers to represent our network topologies. We tested the validity of this framework by comparing a very large set of simulations with different parameters against theoretical values of the same scenarios observing great accuracy. This project was presented to the ns-3 research community in the conference where paper [C] was presented having great acceptance and today the framework is available online in the mentioned link.

With the software framework from paper [C], in paper [D] we reviewed two transmission policies for a set of N D2D cooperating relay devices without inter-connectivity to provide data services to an end device. We made this to address objective 4 from the proposal diagram of Fig. 4. We made this approach since we first considered a device without connectivity covered by only one cloud in our previous works. In this case, we removed this restriction by considering that many devices may reach an end device through a local network. However, this implies that interference should be avoided with a MAC mechanism in a decentralized manner, given that two or more devices may transmit at the same time. We considered independent packet erasure rates for all the links. Although, we evaluated them to homogeneous values for each hop to have less complexity in our results. For

this scenario, the transmission policies between the relays and the end device were: (i) a random forwarding scheme and (ii) recoding with RLNC since we wanted to investigate the gains due to recoding. For these policies and our MAC, each relay senses the wireless medium and transmits with probability p_i , $i \in [1, N]$ and only if it receives a packet from the BS to avoid sending redundant packets. We evaluated $p_i = p$, $\forall i$ to keep the analysis simple and give all the devices the same priority. Later, we made an extensive set of ns-3 simulations, 10^3 for each combination of parameters including packet erasures, number of relays and field sizes; to compare these policies in terms of source, relay and total transmissions required to decode at the destination. Our results showed that ideal access probabilities reduce the number of transmissions. Lower access probabilities below the optimal value increase the number of transmissions from the source to the relays, whereas higher access probabilities above the optimal value increase the number of transmissions from the relays to the destination. These findings allowed to verify policies in reproducible settings which otherwise would have required extensive mathematical analysis. Also, these results show that it is possible to achieve between 50% and 75% gains by enabling recoding and using an access mechanism that assigns equal probability to all the devices in the local network.

3 Thesis Contributions

3.1 Paper A

On the Throughput and Energy Benefits of Network Coded Cooperation

Néstor J. Hernández Marcano, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek
 2014 IEEE Cloud Networking Conference (Cloudnet). IEEE Press, p. 138–142.
 Pages: 5.

Motivation

The benefits of using network coded cooperation in multicast networks for enhanced throughput and reduced energy consumption have been studied in the literature before. However, all prior works assume that the short range links used to cooperate provide a faster and more reliable interface to share missing data packets in a cloud of devices. Given that the achievable rates in cellular networks with former technologies (2G, 3G) were low when compared with for example WiFi, this assumption was reasonable. However, as new emerging technologies such as LTE-A have appeared, this assumption might not be true anymore. Moreover, new proposals in LTE-A consider using D2D communications within the same frequency bands of the cellular connections. This opens the possibility that the achievable data rates for cooperation are the same or possibly less than the cellular connections. Therefore, the goal of this work is to obtain the regions where cooperative transmission scheme with network coding provides a faster throughput and a lower energy consumption than broadcast scheme with network coding.

Paper Content

This work considers a system for multicasting a batch of packets using RLNC to a cloud of devices in a heterogeneous cellular network. To disseminate the batch, two transmission schemes are evaluated: Broadcast with RLNC and cooperation with RLNC. For the cooperative scheme, two phases to obtain the data packets are considered. First, all the packets are transmitted to the cloud where it only matters for a packet to arrive at least at one device. Second, the devices share turns to distribute their packets around the whole cloud. For both schemes, the distribution of the random number of transmissions required to decode the batch is calculated. This permit us to compute the average throughput and energy consumption for transmitting and decoding the batch by assigning rate and energy costs. We include an analysis of

the costs by varying their respective ratios for each scheme for a wide range of packet erasure rates to observe the regions where cooperation presents a better performance than broadcast.

Main Results

In this paper, we showed that a cooperative scheme with network coding provides larger throughput gains than broadcast if the data rate in the local stage doubles the cellular stage one and a large number of devices in the cloud cooperate. Moreover, if the data rates are the same (a possibility when using LTE-A), cooperation still is a preferable choice than using broadcast. For the energy consumption, cooperation is desirable if the energy cost of transmitting a packet in the local stage is the same or less than in the cellular stage. Also, the number of devices with cellular connectivity control a trade-off for the throughput and the energy. A cloud with many devices is more reliable, thus enhancing the throughput. A cloud with less devices with cellular connectivity consumes less energy since there are less devices that need to operate in both stages of the cooperation process.

Related Publications

The analytical framework for this paper is largely extended in paper #[1] of the co-authored papers and paper [B] for other coding schemes and scenarios.

3.2 Paper B

Throughput, Energy and Overhead of Multicast Device-to-Device Communications with Network Coded Cooperation

Néstor J. Hernández Marcano, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek

2016 Wiley Transactions on Emerging Telecommunications Technologies (former European Transactions on Telecommunications). Special Issue: Emerging Topics in Device to Device Communications as Enabling Technology for 5G Systems (ETT). Wiley Press, 2016. pp. 1–17

Pages: 17.

Motivation

To increase the transmission rate of total coded packets and reduce the energy consumed by them, RLNC is utilized to reduce the number of transmissions required to correctly receive a batch of packets. To transmit as less coded packets as possible, practical field sizes of $q = 2^8$ or higher could be of interest. However, for a receiver to be able to decode an encoded dataset, each coded packet the coding coefficients used to create it are appended as signalling. Thus, using a very high field could incur in large signalling. If not properly designed, this might reduce the throughput and increase the energy consumption since the amount of bits for the coding coefficients could be larger than the original packet size. This presents a trade-off in the ideal code selection for data dissemination in a wireless network. Therefore, the first objective of this work was to analyze and apply new proposed codes the avoid the tight trade-off when using RLNC in order to optimize for the throughput and energy in cooperative and broadcast networks. Also, in paper A it was assumed a single fully-connected cloud containing many devices which could be difficult to obtain in practice. Thus, the second objective for this work was to observe the effects of considering many cloud of different sizes.

Paper Content

We review and analyze the application of TC, a recent coding scheme proposed in [54], that permit to obtain the best possible trade-off for minimal overhead when using various fields in the coding scheme design. Here, we defined the overhead in terms of both the average number of transmissions required to decode and the signalling from the coding coefficients. We provide a full mathematical framework to analyze the number of transmissions required to decode for Telescopic Codes, that considers RLNC as a special

case. Later, we analyze the operational trends when considering different cloud sizes. To perform this comparison, we separated the analysis for the cellular and local stage and observed which was the dominating effect.

Main Results

Our proposed schemes attain less than 3% of total mean overhead. This is fairly lower than what can be achieved with RLNC schemes in most of the considered cases and achieving at least 1.5-2X reductions in the total overhead. For the cloud sizes: In the cellular stage, the smallest cloud contributes the most to the total transmission time. In the local stage, the biggest cloud contributes the most to the total transmission time. The homogenous cloud size is the one that provides the minimum amount of transmissions since all clouds take the same amount of time to distribute the data. Furthermore, there is an optimal number of devices per cloud for the homogenous case. Finally, we include a comparison of all our results.

Related Publications

A study only focusing on the benefits of TC was presented in paper #[1] but the full analytical framework with the cloud size analysis is in paper [B]. This framework covers RLNC as a special case which was treated in paper [A]. Currently under preparation, paper #[5] considers the interference effect when no frequency planning is possible only for the broadcast scenario. As side projects, the frameworks from papers #[3] and #[4] would permit to evaluate the proposed solutions with real devices.

3.3 Paper C

Getting Kodo: Network Coding for the ns-3 Simulator *Néstor J. Hernández Marcano, Morten V. Pedersen, Péter Vingelmann, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek*

2016 ACM Workshop on ns-3 (WNS3). ACM Press, p. 101–107.

Pages: 7.

Motivation

In previous works in the network coding literature, the C++11 Kodo library from Steinwurf has been utilized to make real implementations of network coding protocols possible for both the research and industrial communities. While network coding protocols are evaluated in a development process, the simulation stage helps to verify the mathematical analysis, rethink the modeling if observing unexpected effects or accept a design. In the research community, the ns-3 project goal is to establish an open network simulation environment for research. The ns-3 simulator provides the framework to represent standard technologies, perform debugging, code testing and documentation that eases the simulation workflow. Although there has been various initiatives to develop simulations tools in the network coding environment, most of these: (i) are outdated in terms of maintenance and/or functionalities, and (ii) are hard to integrate with standard technologies. Up to this point, there were no network coding libraries that are well-tested and maintained to interact with equivalent network simulation environments such as ns-3. In this work, we provided a set of examples compliant with ns-3 using Kodo as an external library for network coding, where we verify known and expected results from the literature. The purpose of the examples is to serve the research community as the starting point to make their relevant network coding simulations with standard technologies.

Paper Content

First, we presented the theoretical aspects of the encoding, decoding and re-coding operations in RLNC and some application scenarios are mentioned. Second, we described the ns-3 examples project using Kodo and give references to setup guides and tutorials for the reader. We provided the sequential steps to get a Git repository with the examples. Third, we showed how we coupled the Kodo library with ns-3. To achieve this, we introduced a coding layer in an UDP / Internet Protocol (IP) model in ns-3. The network coding operations are implemented by the high-level Kodo C++ bindings. These are

software-wrappers that allow to manage the library in a much simpler way. Later, we describe our three simulation examples that consider two different network topologies. Here, we also indicated how does Kodo interact with ns-3 through two topology helpers. Fourth, we considered an extensive set of ns-3 simulations to verify the model accuracy when compared to theoretical known results.

Main Results

This papers presents ns-3 simulations based on a functional software framework that is available for the research community. The simulations show the Probability Mass Function (pmf) of the distributions for the number of transmissions required to decode for different topologies and system parameters. A large number of simulations, 10^3 , were made in each scenario to get sufficient statistical results. The presented results show the simulations and analytical results match with very high accuracy.

Own Related Publications

This paper provides the ground simulation setup that utilized when analysing the system in paper [D] and paper #[2].

3.4 Paper D

On Transmission Policies in Multihop Device-to-Device Communications with Network Coded Cooperation

Néstor J. Hernández Marcano, Janus Heide, Daniel E. Lucani, Frank H.P. Fitzek

2016 IEEE International European Wireless Conference (EW2016). IEEE Press, p. 350–354.

Pages: 5.

Motivation

Due to increasing data demands in upcoming technologies, a single hop will not be sufficient to reach an end-user from the source of information, given the amount of connected devices. Instead, the end-user may have connectivity through other devices which are connected to the main source in the network that could aid in conveying information to it. Thus, this work focused on reviewing cooperative based mechanisms that can help to relay data and extend connectivity using multihop topologies with D2D communications. Also, this work considered a decentralized approach to access the medium for reducing the inherent interference in these scenarios.

Paper Content

The work considers a system composed of a single source, N intermediate relays and single destination. The destination is provided connectivity to the source through the relays. The transmission process from the source through the relays towards the destination is detailed. A key point in this study was to consider two transmissions policies and a MAC between the relays and the destination. The purpose was to review the advantage of recoding and observe if by controlling the access, some gains could be achieved.

Main Results

This papers shows that 1.5-1.75X gains are possible by using recoding between the relays and destination. The study also shows that ideal access probabilities exist to reduce the required number of transmissions to decode.

Own Related Publications

The simulations to analyze our model in this work, use the setup developed in paper [C].

4 Conclusions

This thesis addresses critical technical challenges from problems the state of the art in multicast D2D cooperative cellular networks with RLNC obtained during the research of the PhD studies. Based on the observed challenges, this thesis presents a network designer the conditions of when, how and how much should a set of devices cooperate to increase the performance of mobile networks to provide quality content to its users. Also, this thesis presents network codes that avoid the overhead trade-off from RLNC in multicast D2D cooperative networks for the first time. To address the challenges in the state of the art, our findings make several proposal.

To achieve at least 2X gains against using broadcast with RLNC, we propose to utilize cooperation when the data rates in the D2D links are at least twice than in the cellular links and when the energy cost for sending and receiving packets within clusters are at least half of the same costs in the cellular networks. However, gains are possible even with the same data rates and energy costs but depends on the packet erasure rates in each stage. To achieve the highest throughput and least energy consumption at the BS, it is required for all the devices inside the clouds to have their connectivity with the cellular network activated. To get the least energy consumption at the devices on average, it is required that only one device in each cloud is connected to the BS and the others of the same cloud not. However, this has the impact of reducing the throughput from the BS. Controlling the number of connected devices to the BS poses a trade-off between throughput and energy. We also propose to use cooperation with clusters of the same size and up to six devices per cluster for practical packet erasure rates. Other cluster sizes are possible, but they most likely reduce the metrics considered in our studies since the clouds take different times to complete in the cellular and local stages.

To avoid the trade-off in RLNC and obtain minimum total overhead, we propose to use telescopic codes with a large portion of the coding coefficients in the binary field for broadcast and the next field for cooperation to obtain less than 3% of total overhead. For these codes, we found that although they provide fair less overhead than RLNC, the achieved overhead for cooperation is slightly higher than for broadcast. This occurred because the recoding operation was defined to be made with smallest field from the first hop, thus impact the total performance. Despite this, this difference is less than one or two percentual units from the total overhead.

We created a reproducible, well-tested and maintained software framework using the Kodo library and the ns-3 simulator for the research commu-

nity to quickly deploy network coding simulations of standard topologies to evaluate simple heuristics in a rapid fashion, thus helping current and future protocol developers in their design process. We verified that the framework produces accurate results. To achieve 1.5-1.75X gains against random forwarding schemes in WLAN using cooperation with D2D, we propose to always decode at the relays and use MAC mechanism to avoid interference using equal access probability for the case of equal packet erasures between the source and the relays.

Besides our proposals, in the following years, future work in the areas investigated in the thesis should consider to make implementations of the proposed solutions in real devices to develop applicable protocols. For this objective, the work in papers #[3] and #[4] could serve as a starting point since they make a deep review of the encoding and decoding speeds of RLNC and variant codes in portable devices, specifically the Raspberry Pi [57], whose Central Processing Unit (CPU) architecture is the same as the mobile devices proposed in this thesis. This will give key performance indicators of the potential of our solutions while allowing us to cover other aspects. Another potential area of improvement from the state of the art is to study resource allocation frameworks in LTE-A or even 5G networks for multicast D2D cooperative networks with RLNC or other network codes. From a theoretical aspect, we considered in this thesis that the interference can be avoided. However, this condition could be difficult to maintain in the near future due to the data demand. Therefore, future studies could consider removing the condition of orthogonal resources for the D2D links and study the impact in our or other metrics to have a broader perspective for future networks. The work in paper #[5] considers this aspect and is currently under preparation for the broadcast scenario. Still, the cooperation scenario remains to be studied. In terms of the transmission policies, even though the simulation analysis allows to review simple heuristics, theoretical studies that review the optimal policies in these scenarios are required to obtain an estimate about the maximum achievable gains.

5 Abbreviations

3GPP 3rd Generation Partnership Project

ACK Acknowledgment

ARQ Automatic Repeat-reQuest

API Application Programming Interface

BS Base Station

cdf Cumulative Density Function

CPU Central Processing Unit

D2D Device to Device

eMBMS Evolved Multimedia Broadcast Multicast Services

FEC Forward Error Correction

GF Galois Field

IoT Internet of Things

IP Internet Protocol

LAN Local Area Network

LDPC Low Density Parity Check

LTE-A Long Term Evolution Advanced

LT Luby Transform

MAC Medium Access Control

MDP Markovian Decision Process

MORE Multipath Opportunistic Routing Engine

M2M Machine to Machine

NC Network Coding

OSI Open Systems Interconnect

OS Operating System

PC Personal Computer

pgf Probability Generating Function
PHY Physical Layer
pmf Probability Mass Function
ProSe Proximity Services
P2P Peer to Peer
QoE Quality of Experience
RLNC Random Linear Network Coding
RS Reed Solomon
SIMD Single Instruction Multiple Data
SINR Signal-to-Interference-plus-Noise Ratio
TCP Transmission Control Protocol
TC Telescopic Codes
UDP User Datagram Protocol
WiFi Wireless Fidelity
WLAN Wireless Local Area Network

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Part II

Papers

Paper A

On the Throughput and Energy Benefits of Network Coded Cooperation

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Frank H.P. Fitzek

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On the Throughput and Energy Benefits of Network Coded Cooperation

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Abstract—Cooperative techniques in wireless mobile networks typically leverage short-range communication technologies, e.g., WiFi, to allow data exchange between devices forming a mobile cloud. These mobile clouds have been considered as a key to reduce the cost of multicast services for the network operators as well as a means to deliver a better quality to the users. In fact, LTE-A includes Device-to-Device communication capabilities to enable such a direct communication between devices. The underlying assumption for attaining the throughput gains in mobile clouds is that the communication rate between devices is typically larger than the data rate from the base station to a receiver. However, while the data rates on cellular technologies have been steadily increasing, short-range communication speeds have remained largely unchanged calling into question these assumptions. This work's goal is to assess the operating regions where the use of cooperation results in a higher throughput and/or energy saving. We consider a multicasting and a cooperative scheme with network coded mechanisms, as they typically outperform uncoded approaches. Our analysis and numerical results show that gains of several fold can be attained even if the data rate of the short-range technologies is moderately larger, e.g., 2x larger, than the cellular link data rate.

Keywords—4G, cooperation, energy, mobile clouds, network coding, throughput

I. INTRODUCTION

Data traffic is expected to grow by an order of magnitude for wireless mobile devices due largely to video services. This presents significant technical challenges for mobile operators to provide high quality of experience to the network users at high data rates, with low delay, while maintaining a low energy consumption in the mobile devices. Thus, mechanisms that can offload infrastructure networks have gathered significant interest from both academia and industry.

To address some of these challenges in multicast transmissions, wireless cooperation between receivers leveraging a separate communication channel to exchange missing data packets (instead of requesting them directly from the cellular infrastructure as in Fig. 1) are known to provide large gains over simply broadcasting the data [1].

This potential for cooperation has resulted in the inclusion of device-to-device (D2D) communication in the 3rd Generation Partnership Project (3GPP) standardization efforts. Beyond offloading the network operator, these cooperative techniques can result in increased reliability, coverage extension, and even increased throughput to end receivers.

In this context, network coding (NC) [2] provides not only a faster and more efficient approach to broadcast the data to the users, as shown by [3], but it simplifies the cooperation process

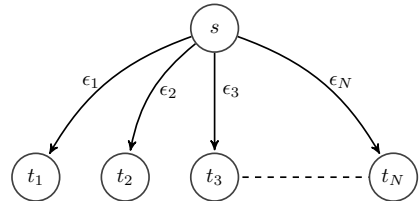


Fig. 1: Single source multiple sink topology of N receivers

since (i) devices need not know the specific packets missing at other devices, only the number of linear combinations available; and (ii) transmissions from a single device during the cooperation process can be used to *heal* a packet at multiple receivers, i.e., each transmission in the cooperation phase can have a larger impact for the end-receivers. This intuition has been exploited in previous work ranging from analysis to optimal policies and practical mechanisms, e.g., [4], [5].

However, the conventional wisdom of such cooperative techniques is that the secondary channel is considerably faster than the channel to the base station. Although this assumption was reasonable in the context of 2G and 3G communications, the much higher data rates achievable in LTE-A (4G) calls this assumption into question. The reason is that alternative technologies for device to device communications, e.g., WiFi, may no longer be faster than LTE-A as their data rates have stayed moderately constant over time. Additionally, if the devices cooperate using D2D of LTE-A the data rate for cooperation will also be limited by the common channel and could be the same data rate in some cases. Thus, the goal of this paper is to revisit the problem of device cooperation focusing on the specific regions of operation where it can bring gains in throughput and energy.

Some of the analysis of mean performance for cooperative schemes has been carried out before, e.g., [4], [6], however this paper provides an in-depth study of the distributions of the number of transmitted packets of different broadcast and cooperative schemes with NC (Section II). Leveraging these distributions, we derive the throughput and energy performance of the various schemes (Section III). In particular, we introduce the natural concept of stable throughput for cooperative schemes. To the best of our knowledge, this has not been considered before because of the conventional assumption that the cellular data rate is the bottleneck in the communication process. Our analysis allows us to determine the regions where cooperation provides gains over broadcasting (Section IV).

II. MODEL AND TRANSMISSION SCHEMES

We consider the problem of reliably transmitting a batch of packets from a source to N receivers using various transmission schemes. The batch constitutes a generation of g packets which we code using random linear network coding (RLNC) with field size q [7]. We assume independent heterogeneous erasure rates on the links from the source to the receivers, $\epsilon_j, j = [1, N]$, to derive the expressions.

We review two transmission schemes namely broadcast RLNC and cooperation with NC. For the cooperative scheme the receivers communicate among themselves to locally repair missing packets. We model the number of transmission as random variables using the geometric distribution as a building block to derive the probability mass functions (pmf) in order to obtain a complete description of the transmission process. We first give a new expression of the pmf for RLNC with no erasures and then compute the pmf for the schemes.

A. RLNC Probability Mass Function

Consider the case of a single source - destination pair without erasures. Let $\mathbb{T}_{RLNC,i}$ be a r.v. for the number of transmissions needed to receive a linearly independent (l.i.) coded packet in a stage of RLNC, i.e. once $i - 1$ l.i. packets have been received. This is a geometric distribution with success probability given by $p_i = 1 - q^{-g+(i-1)}$, $i \in [1, g]$. Following, $\mathbb{T}_{RLNC} = \sum_{i=1}^g \mathbb{T}_{RLNC,i}$ transmissions are necessary to decode g packets. Therefore, the code pmf can be computed using a characteristic function approach to make the analysis more tractable. Consequently, we obtain the pmf for RLNC without erasures in (1), where $P_g = \prod_{i=1}^g p_i = \Pr[\mathbb{T}_{RLNC} = g]$ is the probability of decoding in exactly g transmissions, $\gamma_i = 1 - p_i$ is the probability of receiving a linearly dependent coded packet and $a_i = \prod_{m=1, m \neq i}^g (1 - q^{m-i})^{-1}$ is a scaling factor for γ_i that quantifies the effect of the linear dependence in the decoding probability.

$$f_{\mathbb{T}_{RLNC}}(t; q, g) = \Pr[\mathbb{T}_{RLNC} = t] = \quad (1)$$

$$P_g \sum_{i=1}^g a_i \gamma_i^{t-g}, \quad t \in [g, \infty)$$

B. Broadcast RLNC

As an approximation, we consider the case of finding the required transmissions for the maximum of N independent unicast sessions which makes the results an upper bound since we are excluding the transmissions accounting common coded packets. For each unicast session, we first model a single source - destination pair with erasure ϵ with RLNC and then proceed to calculate the broadcast case. Here, we need to account for g l.i. received packets in t transmissions. Hence, we need to consider all the cases where i l.i. packets are received (with the final success in t , which [8], [9] do not consider) and $t - i$ packets were lost or linearly dependent. For this, we review two main probabilities in the same way as [10]. First, let $\Pr[\mathbb{T}_{S_i} = t]$ be the probability for receiving i coded packets in t transmission (only considering the erasures), then $\mathbb{T}_{S_i} \sim \text{NB}(i, 1 - \epsilon)$. Second, the probability that g coded packets are l.i. in i slots, is $\Pr[\mathbb{T}_{RLNC} = i]$. Subsequently,

the probability of decoding in exactly t slots for a single user with RLNC based unicast with erasure ϵ , $\mathbb{T}_{U,cod}$, is:

$$f_{\mathbb{T}_{U,cod}}(t; \epsilon, q, g) = \Pr[\mathbb{T}_{U,cod} = t] = \quad (2)$$

$$\sum_{i=g}^t \binom{t-1}{i-1} (1 - \epsilon)^i \epsilon^{t-i} f_{\mathbb{T}_{RLNC}}(i; q, g), \quad t \in [g, \infty)$$

Since each receiver just needs to collect different linear combinations to decode the packets, the number of transmissions will be bounded by the receiver that performs the worst in terms of retransmissions, i.e. $\mathbb{T}_{B,cod} = \max_{j=[1,N]} \mathbb{T}_{U_j,cod}$, which we calculate by a c.d.f. approach. For the probability of the maximum being less than or equal to t transmissions, this must occur for every receiver. Then, under the independence assumption, we can compute the c.d.f for broadcast RLNC, e.g. $\Pr[\mathbb{T}_{B,cod} \leq t] = \prod_{j=1}^N \Pr[\mathbb{T}_{U_j,cod} \leq t]$ from (2) with the resulting pmf in (3).

$$f_{\mathbb{T}_{B,cod}}(t; N, \epsilon_1, \dots, \epsilon_N, q, g) = \quad (3)$$

$$\prod_{j=1}^N \left(\sum_{k=g}^t \sum_{i=g}^k \binom{k-1}{i-1} (1 - \epsilon_j)^i \epsilon_j^{k-i} f_{\mathbb{T}_{RLNC}}(i; q, g) \right)$$

$$- \prod_{j=1}^N \left(\sum_{k=g}^{t-1} \sum_{i=g}^k \binom{k-1}{i-1} (1 - \epsilon_j)^i \epsilon_j^{k-i} f_{\mathbb{T}_{RLNC}}(i; q, g) \right)$$

$$, \quad t \in [g, \infty)$$

We notice that the expression in (3) is the general case for low field sizes of the randomized broadcast coding scheme reviewed in [3], since if we let $q \rightarrow \infty$ in (3), then the c.d.f. used to compute (3) tends to the c.d.f. used to compute the mean and variance in section III-B of [3].

C. Cloud Cooperation with Coding

For the cooperation scheme, we consider a mobile cloud composed of H receivers ($H < N$) with cellular connection, the heads and $N - H$ receivers the non-heads, with a local connection to the heads. Packet transmissions takes place in two stages: (i) between source and heads and (ii) between heads and non-heads, which we label the cellular and local stage respectively. For the cellular stage, the source broadcast a coded packet to the heads which receive it *collectively*, i.e. it is enough that one head gets it for the cloud to acknowledge reception, with the stage finishing once the heads get the generation as a group. In the local stage, the heads broadcast recoded packets in a round robin fashion to the non-heads. The local stage finishes once all receivers have decoded the generation.

Under this condition, the distribution of receiving g packets in the cellular stage for the heads, $\mathbb{T}_{C,cod}$ is modeled as $\mathbb{T}_{U,cod}$ but with a success probability given by $1 - \prod_{j=1}^H \epsilon_j$ because all links need to fail for a packet to not be received. In the local stage the heads takes turn to broadcast to the non-heads, which is a particular case of (3). The total number of transmissions for this scheme, $\mathbb{T}_{CC,cod}$, is given by $\mathbb{T}_{CC,cod} = \mathbb{T}_{C,cod}(H, \prod_{j=1}^H \epsilon_j, g, q) + \mathbb{T}_{B,cod}(N - H, \epsilon, g, q)$ where the parentheses notation indicates the evaluation of the pmf with the given parameters.

III. PERFORMANCE METRICS

With the pmf for each scheme from section II, we calculate the moments for the number of transmissions which allows us to compute the throughput and energy.

A. Throughput

We define the throughput in the cloud cooperation scheme for a given erasure rate, generation and field size in the following way:

$$R_{eff,CC} = \frac{g}{\max(T_{s,cel} \mathbb{T}_{C,cod}(H), T_{s,loc} \mathbb{T}_{B,cod}(N - H))} \quad (4)$$

In (4), $T_{s,cel}$ and $T_{s,loc}$ are the duration of a time slot in the cellular and local stages, respectively. The effective rate perceived by a user will be the information sent divided by the completion time. For broadcast RLNC, the throughput is $R_{eff,B} = \frac{g}{T_{s,cel} \mathbb{T}_{B,cod}(N)}$.

B. Energy Consumption

We review the energy spent for the BS and average energy per receiver for the cooperation and broadcast schemes on the coded cases for a given erasure and code parameters. First, the energy consumption for broadcast is as follows:

$$E_{T_x} = E_{cel} \mathbb{T}_{B,cod}(N) ; E_{R_x} = E_{cel} \mathbb{T}_{B,cod}(N) \quad (5)$$

Where $E_{cel} = N_B E_B$ is the energy cost per packet in the cellular stage, N_B is the number of bytes per packet and E_B is the energy per byte proportional to the energy per bit. In a similar way, the energy expenditure for the cooperation schemes is shown in (6).

$$E_{T_x} = E_{cel} \mathbb{T}_{C,cod}(H) \quad (6)$$

$$E_{R_x} = E_{cel} \left(\frac{H}{N} \right) \mathbb{T}_{C,cod}(H) + E_{loc} \mathbb{T}_{B,cod}(N - H)$$

C. Cellular vs. Local Links

The performance of cooperation will depend on the throughput and energy use per bit on the local links vs. that on the cellular links. Therefore, we define the r_t as the ratio between cellular and local throughput, and r_e as the ratio between the cellular and local energy.

$$r_t = \frac{T_{s,loc}}{T_{s,cel}} = \frac{R_{s,cel}}{R_{s,loc}} ; r_e = \frac{E_{b,cel}}{E_{b,loc}} \quad (7)$$

D. Gain Regions

For the analysis with different erasure rates per stage, we define the throughput and energy gains of cloud cooperation against broadcast RLNC from (5) and (6) as shown in (8).

$$G_t = \frac{E\{\mathbb{T}_{B,cod}(N, \epsilon_{cel})\}}{\max(r_t E\{\mathbb{T}_{C,cod}(H, \epsilon_{cel})\}, E\{\mathbb{T}_{B,cod}(N, \epsilon_{cel})\})} \quad (8)$$

$$G_e = 1 - \frac{r_e \left(\frac{H}{N} \right) E\{\mathbb{T}_{C,cod}(H, \epsilon_{cel}) + \mathbb{T}_{B,cod}(N - H, \epsilon_{loc})\}}{r_e E\{\mathbb{T}_{B,cod}(N, \epsilon_{cel})\}}$$

We define throughput gain as the ratio of the cloud cooperation and broadcast RLNC throughputs. The energy gain of cooperation over broadcast is defined as the saving in energy for the devices, since cooperation always save energy at the BS.

IV. NUMERICAL RESULTS

With the obtained expressions, we can evaluate broadcast and cooperation to study the impact on the throughput and energy at the receivers, as we vary the number of users, the ratio between the cellular and local costs, and the erasure rates on the cellular and local links. We use a set of parameters in the following ranges $1 \leq N \leq 50$, $g = \{64, 128\}$, $q = 2^8$ and $0 \leq \epsilon \leq 0.6$. The timeslot duration is set to $T_{s,cel} = 0.5$ ms to conform to the LTE-A E-UTRA [11] and its set of D2D specifications. For the energy, we extracted the energy per bit cost from the energy model in [12] and use a packet size N_B of 500 B.

Fig. 2 shows the throughput as defined in (4) for the different cooperation schemes and broadcast RLNC when the cellular and local data rate are identical. Generally as the number of users increase the sustainable throughput to each receiver decreases. The highest throughput is obtained when the majority are heads, as this reduces the work in the local phase. As the number of non-heads increases the throughput with cooperation tends to that of broadcast, because the transmissions on the local stage becomes the dominating cost.

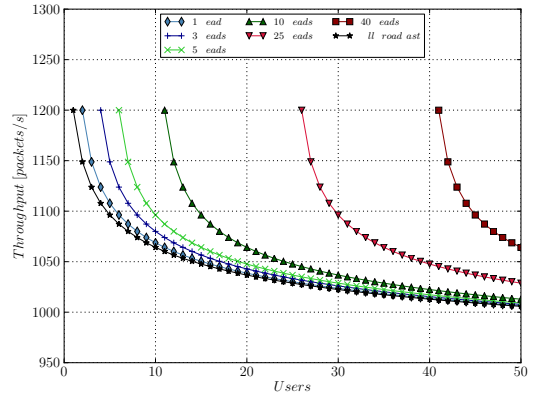


Fig. 2: Schemes throughput for equal data rate costs in the cellular and local link. Used parameters: $g = 64$, $q = 2^8$, $\epsilon = 0.4$, $r_t = 1$

Fig. 3 shows the energy spent per device where the energy costs are the same on the cellular and local links for both schemes. For a low amount of users, the energy consumption for the cooperation scheme is higher than broadcast because the amount of transmissions in the cellular and local links are comparable. As the number of user increases, the number of transmissions in the cellular link tends to g while the transmissions in the local link increases reducing the difference in performance.

Fig. 4 shows how the throughput varies depending on the ratio of the cellular and local data rate. The ratios are

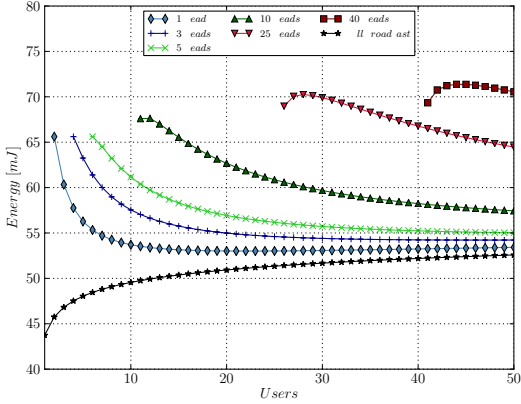


Fig. 3: Schemes energy consumption for equal energy costs in the cellular and local link. Used parameters: $g = 64$, $q = 2^8$, $\epsilon = 0.4$, $r_e = 1$

obtained by fixing the cellular data rate and varying the local data rate. When the local data rate is lower than the cellular rate the cooperative schemes provides lower throughput than the broadcast scheme. Conversely, when the local data rate is higher than the cellular data rate, the cooperative schemes delivers a higher throughput than broadcast. The throughput is highest when the local links rate are twice as faster as the cellular ones. The number of heads controls how much gain can be obtained and where it occurs for a given ratio. When the number of heads decreases, the throughput also diminishes because there are fewer heads each with an independent chance of receiving the packet.

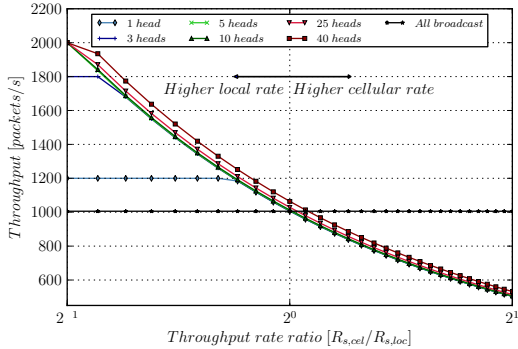


Fig. 4: The throughput of broadcast and cooperation with different number of heads, for different ratios between the data rate on the cellular and local link. Used parameters: $g = 64$, $q = 2^8$, $\epsilon = 0.4$, $N = 50$.

Fig. 5 shows how the energy for the devices changes as ratio between the cellular and local energy per bit changes. The energy cost in the cellular link is fixed and cost on the local link is changed to obtain the different ratios, consequently the energy per bit for broadcast is constant. When the energy

cost for the local links is higher than the cellular energy cost, the cooperative scheme expends more energy than the broadcast scheme. The additional consumption for cooperation comes from the transmissions in the local stage. Contrarily, when the cost of the local links is lower than the cost of the cellular links, then the cooperation scheme uses less energy than broadcast. For the cooperation schemes, the consumption is determined by the number of heads on the cellular stage. For a low number of heads, energy consumption is the lowest because the transmissions on the cellular links are for a few devices only.

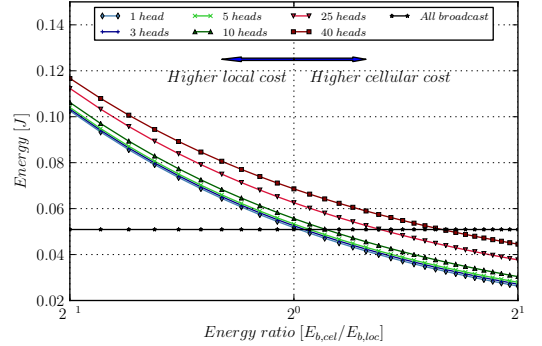


Fig. 5: The energy per generation of broadcast and cooperation with different number of heads, for different ratios between the energy per bit on the cellular and local link. Used parameters: $g = 64$, $q = 2^8$, $\epsilon = 0.4$, $N = 50$.

Fig. 6 shows the regions where cooperation provides a gain in terms of throughput for a wide range of erasure rates on the cellular and local links. The lines show where broadcast and cooperation performs the same, for $r_t = [0.5, 0.8, 1, 1.5, 2]$. In the region below each line, cooperation provides higher throughput than broadcast for that particular r_t . Above the line broadcast performs better. E.g. in the case of a fast local link $r_t = 0.5$ then cooperation provides a gain for almost all considered erasure rates, even in cases where the local erasure rate is much higher than the cellular.

Fig. 7 shows the regions where cooperation provides a gain in terms of energy saving on the devices for various erasure rates on the cellular and local links. The lines show where broadcast and cooperation performs the same, for $r_e = [0.5, 0.75, 1, 1.5, 2]$. In the region below each line, cooperation provides a lower energy per bit than broadcast for that particular r_e . Above the line broadcast performs better.

V. CONCLUSIONS

This work revisits the problem of wireless cooperation with network coding on cellular systems for multicast sessions in light of the increased data rates of current 4G and future 5G mobile networks and the stagnant data rates in short-range technologies, e.g., WiFi. This is particularly relevant because it breaks with the common assumption that the cooperative cluster can communicate locally at much higher data rates than the direct link to the cellular base station.

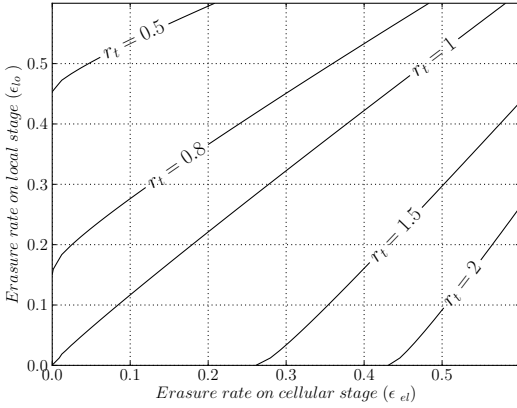


Fig. 6: For different values of r_t the lines indicate where cooperation and broadcast provide the same throughput for various erasure rates on the cellular and local links. Below the each line, cooperation performs better for the respective r_t . Used parameters: $g = 128$, $q = 2^8$, $H = 40$, $N = 50$.

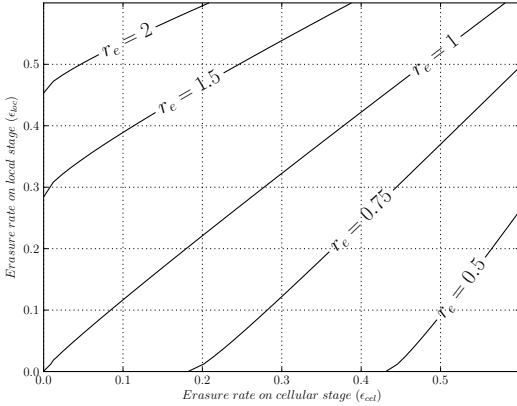


Fig. 7: For different values of r_e the lines indicate where cooperation and broadcast provide the same energy per bit for various erasure rates on the cellular and local links. Below the each line, cooperation performs better for the respective r_e . Used parameters: $g = 128$, $q = 2^8$, $H = 40$, $N = 50$.

More specifically, we presented an in-depth study of the specific operating regions where cooperation provides gains in throughput and energy over coded broadcasting techniques. Our numerical results showed that gains can be achieved even if the long-range and short-range technologies transmit at comparable data rates. More importantly, we showed that cooperation can provide several fold gains to the best broadcasting option (network coded broadcast) as long as the short-range link is at least twice as fast as the long-range one. Finally, our results showed that a moderate number of heads (e.g., three or more) per cooperative cluster is enough to yield the high throughput gains while maintaining a low energy consumption

at the receivers. The latter is not possible if a large fraction of the cooperative cluster is actively receiving directly from the base station with only a few exchanges needed during the cooperation process.

Future work shall focus on protocol design for cooperative schemes in highly-dense scenarios as well as implementation and evaluation of the most promising schemes in Aalborg University's Raspberry Pi testbed [13].

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Paper A.

Paper B

Throughput, Energy and Overhead of Multicast Device-to-Device Communications with Network Coded Cooperation

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Paper B.

SPECIAL ISSUE PAPER

Throughput, energy and overhead of multicast device-to-device communications with network-coded cooperation

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ABSTRACT

Cooperation strategies in mobile networks typically rely in short-range technologies, like LTE-A device-to-device communications, for data exchange between devices forming mobile clouds. These communications provide a better device experience because the clouds offload the network. Nevertheless, this assumes that the throughput gains and energy savings in multicasting are much larger between devices than the base station to the receivers. However, current mobile networks suffer from many different issues varying the performance in data rates, which calls into question these assumptions. Therefore, a first objective of this work is to assess the operating regions where employing cooperation results in higher throughput and/or energy savings. We consider multicast scenarios with network-coded mechanisms employing random linear network coding (RLNC). However, although RLNC is good for low amount of transmissions in multicast, it has an inherent overhead from extreme high or low field-related caveats. Thus, as a second objective, we review and propose the application of new network codes that possess low overhead for multicasting, by having a short representation and low dependence probability. We provide an analytical framework with numerical results showing (i) gains of several fold can be attained even if the in-device data rates are moderately larger ($2\times$) than the cellular link data rate and (ii) that is feasible to attain less than 3% total mean overhead with the proposed codes. This is fairly lower than what can be achieved with RLNC schemes in most of the considered cases and achieving at least $1.5\text{--}2\times$ gains. Copyright © 2016 John Wiley & Sons, Ltd.

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1. INTRODUCTION

Data traffic is expected to grow by an order of magnitude for wireless mobile devices to support many data demanding services as shown in Figure 1 [1]. Common services of this type are video multicasting or local multimedia content sharing. From the perspective of the mobile users, high perceived quality and a low battery drain are important. For operators, their goal is to serve the highest number of users with the least amount of network resources and energy consumption from their infrastructure. In this scenario, both multicast and cooperation provide better performance than unicast, because several devices are served with the same communication resources.

Then, mechanisms that can offload network infrastructures have gathered significant interest from both academia and industry. Thus, there is a general interest

from both academia [2, 3] and industry [4] in finding strategies that reduce mobile network usage by offloading the infrastructure to other types of short-range communications like device-to-device (D2D) or Wi-Fi. For this purpose, wireless cooperative *mobile clouds* [5, 6] are formed by receivers helping the cellular network by locally exchanging missing data packets instead of directly requesting them from it. Thus, cooperative techniques result in increased reliability, coverage extension and even increased throughput to end receivers. This potential has resulted in the inclusion of D2D communications in the 3rd Generation Partnership Project standardisation efforts. To recover from packet erasures in the wireless medium, typically rateless codes are employed as a forward error correction technique. Nevertheless, although they provide benefits for a broadcast scenario, they cannot be deployed for cooperative communications without affecting their

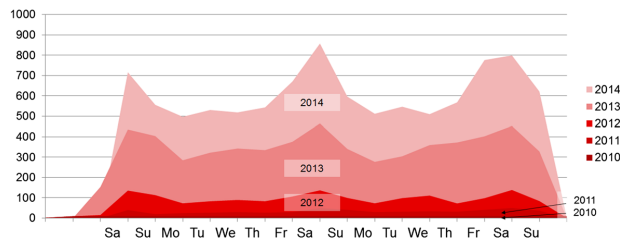


Figure 1. Average Oktoberfest data load for the 2010–2014 period (generic data units).

performance or decoding the data for each hop. Thus, there is a need for code schemes to overcome these drawbacks.

In this context, network coding [7], and particularly random linear network coding (RLNC) [8], not only provides a faster and more efficient approach to broadcast the data to the users, as shown by [9], but also simplifies the cooperation process because (i) the devices only need to know the number of linear combinations available and (ii) transmissions from a single device during the cooperation process can have a larger impact for the end receivers, given that a single transmission can help different devices at the same time. This intuition has been exploited in previous works ranging from analysis to optimal policies and practical mechanisms, for example, Khamfroush *et al.* [10, 11].

However, the underlying assumption is that the cooperative channel is considerably faster than the channel to the base station and that energy costs are much lower because of proximity. Although this assumption was reasonable long ago, now the much higher data rates achievable in Long Term Evolution-Advanced (LTE-A) call this assumption into question. Also, if the devices cooperate using D2D of LTE-A, the data rate for cooperation will also be limited by the common channel and could be the same data rate in some cases. Thus, one goal of this paper is to review the problem of device cooperation focusing on the specific regions of operation where it can bring gains in throughput and energy.

Some of the analysis of mean performance for cooperative schemes has been carried out before, for example, Heide *et al.* [6, 12]; however, this paper provides a comprehensive study of the distributions of the number of transmitted packets for various scenarios. We define the natural concept of stable throughput for cooperative schemes. To the best of our knowledge, this has not been considered before because of the conventional assumption that the cellular data rate is the bottleneck in the communication process.

A second important factor that may affect the performance of the network is the coding scheme choice. The reason being that if a code does not employ resources properly, it reduces even more the benefits of throughput and energy in the short-range links. Here, RLNC considers creating linear combinations from a single network flow to distribute data between many devices. In order to reduce complexity and delay, transmissions of

packet batches from the original data, called generations, were introduced in [13] as a technique to accomplish this. RLNC's flexibility to adapt to different network topologies makes it an interesting choice for upcoming networking protocols. Although, given that the random coefficients are picked from a single field, RLNC-based techniques have the caveat of introducing overhead due to mainly two reasons in the coding process. First, transmissions of linearly dependent (l.d.) packets occur due to the random selection of the coefficients [14, 15]. Second, in order to later perform decoding, typically the easiest goes for the coding coefficients to be appended to each coded packet before being sent through the network.

Different works have been made to observe the effects of RLNC parameters, for example, generation and field size [16], not only for the overhead but also for other metrics such as energy consumption and processing speed [17] among others. Variants of RLNC have been proposed to exploit a particular code structure to obtain a low overhead without compromising other metrics [18]. More recently, in [19], *telescopic codes* (TC) were introduced applying composite extension fields within a single generation, with the goal of reducing the total overhead while preserving recoding. Its parameters and performance were analysed for an ideal unicast scenario, but their potential for unreliable multicast scenarios was not explored.

In [20] and [21], the authors develop new optimised transmission and coding schemes based on RLNC for content distribution. However, they only consider broadcast and exclude cooperation. Also, these studies have a strong focus on video streaming, while in our case, we deal with distributing data in general. Furthermore, they do not consider the overhead of the code. In [22–25] can be found the advantages of employing multicast schemes with D2D capabilities. Although, these works do not consider both cooperation and network coding at the same time, making it difficult to evaluate the benefits of network coding in these scenarios. In this work, we pursue two goals: we (i) analyse the throughput and energy gains of network-coded cooperation and (ii) propose the employment of TC as a technique for minimising the overhead in heterogeneous, unreliable, cooperative networks. We provide a full analysis with a set of numerical results for both the region gains with RLNC and the use of TC for low overhead. We make this analysis for three scenarios in multicast sessions,

namely, broadcast, single cloud cooperation and multiple clouds cooperation for D2D communications, because they provide more benefits than others like unicast. Moreover, for the employment of TC, we compute the set of composite fields required to minimise the total overhead, which we define for broadcast and single cloud cooperation.

Our work is organised as follows: Section 2 introduces our system and general assumptions. Section 3 describes the code schemes and scenarios that we review indicating how the information is conveyed through the network. Analysis of the proposed coding schemes and transmission scenarios is made in Section 4. Later, Section 5 shows the considered metrics in our study with the numerical results provided in Section 6. Final conclusions are presented in Section 7. The proofs of the used lemmas and corollaries in our study are in the Appendix.

2. SYSTEM MODEL

We consider the problem of reliably transmitting a set of packets from a source to N receivers in a cellular network under various transmission scenarios. The set constitutes a generation of g packets, which we code using RLNC with field size q . We consider a general topology as shown in Figure 2 where receivers might form D2D-based mobile clouds with multicast capabilities. Devices that are relatively close together create fully interconnected clouds.

In general, we may have C clouds, where each cloud has N_n users with $n \in [1, C]$ and $N = \sum_{n=1}^C N_n$. Here, in each cloud, we differentiate two types of devices. First, we refer as *heads* the devices with both cellular connectivity to the source and all others in the cloud. Then, we have $H_n \leq N_n$ heads per cloud. Second, the *non-heads* are the devices without a cellular connection but only to all others, for example, $N_n - H_n$ non-heads per cloud. For our study, we briefly observe the dominating regimes for heterogeneous cloud sizes to notice that the homogeneous cloud size provides the best performance in terms of total transmission time. Therefore, we review the case of having

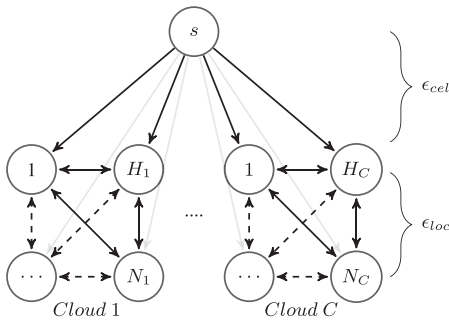


Figure 2. Topology of C device-to-device mobile clouds.

a homogeneous cloud size, for example, the same number of users in each cloud $N_n = N_{uc} \forall n$, giving $N = C \times N_{uc}$, because this is the ideal operational regime.

We consider independent packet erasure rates on the connectivity links from the source to the heads, ϵ_{jn} , $j \in [1, H_n]$, $n \in [1, C]$; for example, the packet reception distribution of receiver j is $Bernoulli(1 - \epsilon_{jn})$ and is independent from all others. We will provide the general expressions for scenario distributions with heterogeneous cellular links, but for evaluation purposes, we will consider all these erasures equal to ϵ_{cel} . Similarly, inside any cloud, all the connections can be regarded as bidirectional symmetric channels via D2D. These links have homogeneous, independent and identically distributed erasure rates, which we consider equal to ϵ_{loc} for simplicity.

To guarantee interference management and proper content delivery, we assume an underlay D2D mobile network. In this way, we review the transmission scenarios once a previous and arbitrary cellular network resource allocator has assigned the communications resources in it. Once network management has been addressed, packets are either sent under a broadcast ($N_{uc} = 1$), multiple cloud ($1 < N_{uc} < N$) or single cloud ($N_{uc} = N$) cooperation transmission scenarios.

Thus, in any scenario, for convenience, we consider that $C + 1$ physical communication resources have already been allocated. Nevertheless, if $K < C + 1$ are only available, standard cellular techniques such as frequency reuse patterns can be employed. Then, two clouds using the same frequency will be geographically separated long enough to ensure the reuse of communication resources without causing interference. We consider this to perform the transmissions between the source and all the clouds through *multicast groups*. First, a multicast group is created between the source and all cloud heads to transmit the content to each cloud collectively. Second, C multicast groups are created between the heads of each of the C clouds and their respective non-heads, to cover missing packets. In this stage, the network controller is in charge of the coordination regarding on how the nodes must share their content into its own cloud.

Inter-cloud interference is defined as the reception of a transmission from a cloud where a receiver does not belong, which occurs when a transmission of that receivers cloud has been made during the same time slot. The interference generates a reduction in the signal-to-interference-plus-noise ratio, which increases the erasure rate and degrades the reception, possibly forcing retransmissions. Hence, we assume that cloud transmissions take place in orthogonal resources to ensure that inter-cloud interference does not occur. In case there are no available resources, techniques such as frequency reuse planning from mobile networks help to avoid this interference. For example, two clouds using the same frequency will be geographically separated enough to ensure there is no interference, making possible to reuse communications resources.

We consider the scenario where an acknowledgment (ACK) is sent only in two cases: first, when a receiver has collected g linearly independent (l.i.) coded packets and

second, for the cooperative case, when a cloud has g i.i. coded packets as a group. The ACK is sent through a reliable communications channel. Thus, only one ACK per generation of packets per receiver is sent. This makes a total of N feedback packets, differing from the case where ACKs are sent on a per-packet and per-receiver basis, which would result in $g \times N$ feedback packets. In other words, this reduces the feedback transmissions by a factor of g . If feedback is not wanted (or possible), a fixed number of extra transmissions can be sent ensuring some target reliability level, for example, 99%. However, because the number of transmissions is fixed, such an approach will lead to an additional transmission overhead particularly if the channel is time varying.

3. CODING SCHEMES AND TRANSMISSION SCENARIOS

In this section, we first consider and describe two coding schemes. Afterwards, we describe the three transmission scenarios considered in our study, namely, broadcast, single cloud cooperation and multiple clouds cooperation. We review them going from the simplest to the most elaborated scenario. Regarding the coding schemes, first, in all the scenarios, the source or the heads employ RLNC as a coding scheme. Second, for only broadcast and single cloud cooperation, we employ TC [19]. These types of codes possess very low overhead. The reason is that they are tailored for a given network to provide the best trade-off between both the overhead caused by (i) transmissions of l.d. packets and (ii) sending the coding coefficients for any receiver to be able to decode.

To accomplish this, TC relies on *composite extension finite fields*. This type of fields enables an encoder to create coded packets in an RLNC fashion but with some differences. The key idea for TC with composite fields is the following: Instead of picking all coding coefficients from a single field q inside a generation of size g , the encoder selects each coding coefficient v_j , $j \in [1, g]$ in the generation from $GF(q_j)$. Here, q is a vector that contains all the field sizes employed for each of the coding coefficients. Each of the field sizes follows a specific pattern. The chosen pattern makes compatible finite fields arithmetics from different fields in the same generation. In the subsequent sections, we give a brief description of RLNC because it is well known in the network coding literature. However, we provide further details for TC because they were recently introduced. Also, as we will see in our framework, RLNC will be regarded as a special case of TC that occurs when $q_i = q \forall i \in [1, g]$. Thus, we will focus the following section on describing TC and its operations.

3.1. Coding schemes

3.1.1. Random linear network coding.

For this conventional coding scheme, we may create an encoded packet, create a recoded packet from a previous set or decode any set g coded packets performing

Gaussian elimination on the $g \times g$ coding matrix. In general, we consider a field size q from which we take the coding coefficients and perform predefined Galois Field (GF) arithmetics. As follows, we will see that this is a special case of TC.

3.1.2. Telescopic codes.

We consider coding g packets, $m_{j,j} \in [1, g]$ in the generation, each of size B bits. We define q as a vector containing each of the field sizes q_j , we assume $q_j \leq q_{j+1}, \forall j \in [1, g]$ without loss of generality. Then, coded packets are generated in a similar fashion as with RLNC. However, each coding coefficient in an encoding vector v is chosen uniformly at random from a finite field $GF(q_j), j \in [1, g]$ differing from RLNC. To keep valid field arithmetics, TC are based on composite extension finite fields of the form \mathbb{F}_{2^k} with $k \in [1, 2, 4, 8, \dots]$ in general. The key idea in composite extension fields is to design the arithmetic operations of a new extended finite field from the operations of a base field. With the extended field, we can continue the process and create another extension and so on. These fields are designed to allow compatibility for the operations performed among them. The composite fields are defined and described in [19]. Nevertheless, we give a brief overview of its operations to have a description for our analysis in Section 4.

3.1.3. Encoding.

A generic coded packet, c_i , is generated by an encoder by mixing linear combinations of g packets. Here, packet m_j is regarded as an element from $GF(q_j)$ and is multiplied by a coding coefficient $v_{i,j}$ chosen uniformly at random from $GF(q_j)$. Thus, a resulting coded packet of size B and its coding can be expressed as:

$$c_i = \bigoplus_{j=1}^g v_{i,j} \otimes m_j \quad (1)$$

$$|v_i| = \sum_{j=1}^g |v_{i,j}| = \sum_{j=1}^g \lceil \log_2(q_j) \rceil \text{ [bits]} \quad (2)$$

3.1.4. Decoding.

To perform decoding, we define $c = [c_1 \dots c_g]^T$ and $m = [m_1 \dots m_g]^T$. Decoding reduces to solve the linear system $c = V \cdot m$ using Gaussian elimination [26]. Here, the coding matrix V contains any set of g i.i. packets c_i as rows as follows:

$$V = \begin{bmatrix} v_1 \\ \vdots \\ v_g \end{bmatrix} = \begin{bmatrix} v_{1,1} & \dots & v_{1,g} \\ \vdots & \ddots & \vdots \\ v_{g,1} & \dots & v_{g,g} \end{bmatrix} \quad (3)$$

The decoder begins removing the contributions of the smallest field pivot elements, for example, leftmost elements in the main diagonal of (3). Once that information

is known to the decoder, it proceeds in the same way for the next upper field in the composition using operations of the current field and so on to obtain the original set of packets [19].

3.1.5. Recoding.

Given the picking of elements from different fields, recoding needs to be properly defined to ensure that the coefficients of a recoded packet cannot be differentiated from a single coded one. Different approaches are described in [19]. For the scope of this study, we considered recoding in the lowest available field in the generation because it preserves recoding with low overhead in the encoding vector. Nevertheless, the major problem in this approach is the increase of more l.i. packets for the last transmissions in a given generation. In this way, let us define a generic recoded packet as \tilde{c}_i and its corresponding encoding vector as \tilde{v}_i as follows:

$$\tilde{c}_i = \bigoplus_{j=1}^g w_{i,j} \otimes c_j \quad (4)$$

$$\tilde{v}_i = \bigoplus_{j=1}^g w_{i,j} \otimes v_j \quad (5)$$

In (4) and (5), $w_{i,j}$ is the coding coefficient that multiplies c_j , uniformly and randomly chosen from $\min(q)$. Any decoder that collects $\tilde{c}_i, i \in [1, g]$ l.i. packets, with their \tilde{v}_i , will be able to decode the whole generation as described in Section 3.1.4.

3.2. Transmission scenarios

3.2.1. Broadcast.

For broadcast, $N_{uc} = 1$, the source generates an encoded packet and later attaches the coding coefficients values and sends it to all receivers through the erasure channels described in Section 2. When a packet successfully arrives at a receiver, it checks if the packet is l.i. from all its previous. If not, it discards it. In case of being l.i., the receivers add it to its coding matrix. This process is repeated until all receivers have collected their required combinations. An ACK is sent through the feedback channel from the last receiver after it obtains its final combination. In this scheme, recoding is not used.

3.2.2. Single cloud cooperation.

In a single cloud cooperation scenario, $N_{uc} = N$ and packet transmissions take place in two stages. First, the source broadcasts coded packets to the heads through the cellular network, that is, the cellular stage, and second, internally between receivers, which have missing packets, in a network-coordinated fashion, that is, the local stage. For the cellular stage, the source broadcast coded packets for the cloud heads, because it is enough to obtain coded packets collectively to later recode them. Once the cellular stage has ended, for example, the g l.i. packets are in

the cloud, there will be receivers that do not exactly have this quantity of packets to decode. To manage this, in the local stage, each head broadcasts recoded packets in a coordinated way to ensure all receivers obtain their remaining packets. For the case of TC, recoding will be performed in the lowest field. This stage finishes once all receivers have decoded the generation and any device in the cloud sends and an ACK through the feedback channel to the sender.

3.2.3. Multiple clouds cooperation.

For a cloud cooperation scenario, $1 < N_{uc} < N$, packet transmissions go in a similar way as before. However, two main differences exist. First, in the cellular stage, packets are broadcasted to the heads multicast group, instead of all in a single cloud. Hence, we use one multicast channel. Second, in the local stage, the C set of heads broadcasts recoded packets to all the other users inside their respective multicast groups. Again, this performed in a network-coordinated way to ensure all receivers obtain their remaining packets. This stage finishes once all receivers in all clouds have g l.i. coded packets and an ACK through the feedback channel to the sender.

4. SCENARIOS ANALYSIS

We proceed to study the underlying probability distributions for the number of transmissions required to decode either RLNC or TC within their respective transmission scenarios. With the statistical description of the transmissions, we perform two types of studies. First, we identify the regions where cooperation performs better than broadcast in terms of throughput and energy when RLNC is used. Second, for TC, we perform an overhead analysis for the transmission scenarios and evaluate them for three schemes that can be used with TC.

For the code and each transmission scenario, we model the number of transmissions to decode as a random variable to derive its probability mass function (pmf). We perform this in order to obtain reasonable approximations of the linear independence, erasure and transmission processes and also to separate the effect of the code from the scenario. We first give an expression of the pmf for RLNC, later we incorporate erasures in the process and finally compute the pmf for the transmission scenarios.

4.1. Coding scheme distributions

To calculate the distribution and pmf for either an RLNC or TC scheme in a generic fashion, we derive a framework for the pmf of TC distribution, and we will make the proper evaluations to differentiate with RLNC.

We first consider a single source-destination link without erasures. The process for obtaining each new l.i. packet can be modelled by the Markov Chain in Figure 3. This chain comprises $g + 1$ states. First, state i with $i \in [1, g]$ is the case where the i -th l.i. coded packet has not been received

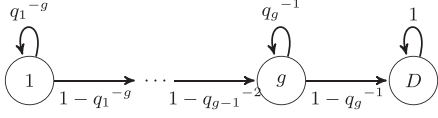


Figure 3. Absorbing Markov Chain for telescopic codes.

by the destination. Then, D is the absorbing state where decoding is performed.

The transition probabilities of each state depend not only on the amount of previously received l.i. combinations but also on the field chosen to represent the i -th coding coefficient. The model in Figure 3 is a reasonable approximation as described in [19] because, in the decoding process, non-received pivots from the lowest fields dominate the transition probabilities and tend to appear first.

We use a probability-generating function (pgf) approach with the key idea that each stage of the Markov Chain of TC in Figure 3 can be modelled as a geometric distribution and then compute the pmf from operations in the more tractable pgf domain.

Lemma 4.1 (*Telescopic codes probability mass function*). Consider the case of a single source-destination link without erasures that employs TC of generation size g field size q . Let \mathbb{T}_{TC} be the random number of transmissions required to decode. Then, the pmf of \mathbb{T}_{TC} for the probability of decoding in exactly t transmissions is

$$f_{\mathbb{T}_{TC}}(t; g, \mathbf{q}) = \Pr[\mathbb{T}_{TC} = t] = P_g \sum_{l=1}^L \sum_{n=1}^{m_l} a_{l,n} \binom{t-g+n-1}{t-g} \gamma_l^{t-g}, \quad t \in [g, \infty) \quad (6)$$

where in (6), $P_g = \Pr[\mathbb{T}_{TC} = g]$ is the probability of decoding in exactly g transmissions, $\binom{n}{k}$ is the binomial coefficient defined as $\frac{n!}{k!(n-k)!}$ with $n \geq k$ and γ_l , $l \in [1, L]$ is one of the L distinct probabilities from the Markov Chain, which is repeated m_l times in the resulting Markov Chain. The $a_{l,n}$, $l \in [1, L]$, $n \in [1, m_l]$ are the residues of the pgf of (6) given by

$$a_{l,n} = \frac{\lim_{z \rightarrow \gamma_l} \frac{d^{m_l-n}}{d(z^{-1})^{m_l-n}} \left(\frac{G_{\mathbb{T}_{TC}}(z^{-1})(1-\gamma_l z^{-1})^{m_l}}{P_g z^{-g}} \right)}{(m_l - n)!(-\gamma_l)^{m_l-n}} \quad (7)$$

Proof. The proof is in the Appendix. \square

Corollary 4.1.1 (*RLNC Distribution*). The distribution and pmf for RLNC is given by

$$\begin{aligned} f_{\mathbb{T}_{RLNC}}(t; g, \mathbf{q}) &= \Pr[\mathbb{T}_{RLNC} = t] \\ &= P_g \sum_{i=1}^g a_i \gamma_i^{t-g}, \quad t \in [g, \infty) \end{aligned} \quad (8)$$

where in (8), the a_i are given as follows:

$$a_i = \prod_{m=1, m \neq i}^g \frac{1}{1 - q^{m-i}} \quad (9)$$

Proof. The proof is in the Appendix. \square

We include the analysis for a generic erasure ϵ by following a procedure, as made in [27], that considers all the disjoint cases by the law of total probability, where i l.i. coded packets were received in t transmissions and $t - i$ coded packets were received and l.i. The successful receptions are accounted by the negative binomial distribution[†] and the linear independence by (6). Then, the pmf for a unicast session with TC and erasures, \mathbb{T}_U , can be expressed as follows:

$$f_{\mathbb{T}_U}(t; g, \mathbf{q}, \epsilon) = \Pr[\mathbb{T}_U = t] = \sum_{i=g}^t \binom{t-1}{i-1} (1-\epsilon)^i \epsilon^{t-i} f_{\mathbb{T}_{TC}}(i; g, \mathbf{q}), \quad t \in [g, \infty) \quad (10)$$

4.2. Broadcast distribution

For broadcast, we can regard its pmf as the case of finding the required transmissions for the maximum of N independent parallel unicast sessions. This results in an upper bound because we exclude other policies that take advantage of common coded packets. Because each receiver just needs to collect different linear combinations to decode the packets, the number of transmissions will be bounded by the receiver that performs the worst. In this way, the number of transmissions for broadcast is given by $\mathbb{T}_B = \max_{j \in [1, N]} \mathbb{T}_{U_j}$, where \mathbb{T}_{U_j} is the distribution on which pmf is obtained from (10). We review this and prove it in the following lemma.

Lemma 4.2 (*Broadcast TC probability mass function*). Consider the case of a broadcast scenario with heterogeneous packet erasure rates ϵ_j , $j \in [1, N]$ that employs TC of generation size g and field sizes q . Let \mathbb{T}_B be the random number of transmissions required to decode. Then, the pmf of \mathbb{T}_B for the probability of decoding in exactly t transmissions is

[†]We use the definition of the negative binomial distribution that accounts for the random number \mathbb{T} of Bernoulli trials of success probability p required to attain n successes. Then, $\mathbb{T} \sim NB(n, p) \implies \Pr[\mathbb{T} = t] = \binom{t-1}{n-1} p^n (1-p)^{t-n}$, $t \in [n, \infty)$.

$$f_{\mathbb{T}_B}(t; N, g, \mathbf{q}, \epsilon_1, \dots, \epsilon_N) = \prod_{j=1}^N \left(\sum_{k=g}^t \sum_{i=g}^k \binom{k-1}{i-1} (1-\epsilon_j)^i \epsilon_j^{k-i} f_{\mathbb{T}_{TC}}(i; g, \mathbf{q}) \right) - \prod_{j=1}^N \left(\sum_{k=g}^{t-1} \sum_{i=g}^k \binom{k-1}{i-1} (1-\epsilon_j)^i \epsilon_j^{k-i} f_{\mathbb{T}_{TC}}(i; g, \mathbf{q}) \right), \quad t \in [g, \infty) \quad (11)$$

where in (11), $f_{\mathbb{T}_{TC}}(t; g, \mathbf{q})$ is the TC pmf given by (6).

Proof. The proof is in the Appendix. \square

Corollary 4.2.1 (Homogeneous erasures in broadcast). *The pmf of broadcast TC with homogeneous erasure rates, $\epsilon_1, \dots, \epsilon_N = \epsilon$, is*

$$f_{\mathbb{T}_B}(t; N, g, \mathbf{q}, \epsilon) = \left(\sum_{k=g}^t \sum_{i=g}^k \binom{k-1}{i-1} (1-\epsilon)^i \epsilon^{k-i} f_{\mathbb{T}_{TC}}(i; g, \mathbf{q}) \right)^N - \left(\sum_{k=g}^{t-1} \sum_{i=g}^k \binom{k-1}{i-1} (1-\epsilon)^i \epsilon^{k-i} f_{\mathbb{T}_{TC}}(i; g, \mathbf{q}) \right)^N, \quad t \in [g, \infty) \quad (12)$$

Proof. It can be easily verified that evaluating (11) with homogeneous erasure rates, $\epsilon_j = \epsilon \forall j$, and doing the corresponding algebra, one obtains (12). \square

4.3. Single cloud cooperation distribution

For single cloud cooperation, we consider its random number of transmissions for decoding, \mathbb{T}_{SCC} , as the sum of two random number of transmissions. First, we consider the random number of transmissions for the cloud to obtain g i.i. coded packets in the cellular stage, $\mathbb{T}_{SCC,cel}$. Second, we add the number of transmissions in the local stage required for all the devices to share their content, $\mathbb{T}_{SCC,loc}$, which is a particular case of broadcast under the proper evaluation. Hence, $\mathbb{T}_{SCC} = \mathbb{T}_{SCC,cel} + \mathbb{T}_{SCC,loc}$. We give a formal definition of this distribution and its proof in the following lemma.

Lemma 4.3 (Single cloud cooperation TC distribution). *Consider the case of a single cloud cooperation scenario that employs TC of generation size g and field sizes q . The cloud is composed of H heads from N devices with $H \leq N$. The heads have heterogeneous packet erasure rates ϵ_j , $j \in [1, H]$ for the links between the source and them. All devices inside the cloud have a homogeneous packet erasure rate ϵ_{loc} for all their $\frac{N(N-1)}{2}$ connection links between them. Then, the distribution for the random number of transmissions required for decoding is given by*

$\mathbb{T}_{SCC} = \mathbb{T}_{SCC,cel} + \mathbb{T}_{SCC,loc}$ where each term is given as follows:

$$\mathbb{T}_{SCC,cel} = \mathbb{T}_U \left(g, \mathbf{q}, \prod_{j=1}^H \epsilon_j \right) \quad (13)$$

$$\mathbb{T}_{SCC,loc} = \begin{cases} \mathbb{T}_B(N-H, g, \mathbf{q}, \epsilon_{loc}), & H < N \\ \mathbb{T}_B(N_{loc}, g_{loc}, \mathbf{q}, \epsilon_{loc}), & H = N \end{cases} \quad (14)$$

$$N_{loc} = N - \left\lfloor P_g \sum_{j=1}^N (1-\epsilon_j)^g \right\rfloor \quad (15)$$

$$g_{loc} = \max_{j \in [1, N]} \left(g - \left\lfloor (1-\epsilon_j) \sum_{i=1}^g p_i \right\rfloor \right) \quad (16)$$

where in (13) and (14) the parenthesis notation indicates the evaluation of the respective distribution with the given parameters. In (15) and (16), P_g and p_i are respectively the probabilities of linear independence at g transmissions and in each stage of the TC Markov Chain. Both are defined in the proof of Lemma 4.1.

Proof. The proof is in the Appendix. \square

Corollary 4.3.1 (Homogeneous conditions in single cloud cooperation). *The distribution of single cloud cooperation TC with homogeneous erasure rates, $\epsilon_1, \dots, \epsilon_H = \epsilon_{cel}$, is*

$$\mathbb{T}_{SCC,cel} = \mathbb{T}_U(g, \mathbf{q}, \epsilon_{cel}^H) \quad (17)$$

$$\mathbb{T}_{SCC,loc} = \begin{cases} \mathbb{T}_B(N-H, g, \mathbf{q}, \epsilon_{loc}), & H < N \\ \mathbb{T}_B(N_{loc}, g_{loc}, \mathbf{q}, \epsilon_{loc}), & H = N \end{cases} \quad (18)$$

$$N_{loc} = N - \left\lfloor P_g N (1 - \epsilon_{cel})^g \right\rfloor \quad (19)$$

$$g_{loc} = g - \left\lfloor (1 - \epsilon_{cel}) \sum_{i=1}^g p_i \right\rfloor \quad (20)$$

Proof. By evaluating Equations 13–(16) with $\epsilon_j = \epsilon_{cel}$, $\forall j$ \square

4.4. Multiple clouds cooperation distribution

For multiple clouds cooperation, we consider its random number of transmissions for decoding, \mathbb{T}_{MCC} , again as the sum of two random number of transmissions in a cellular and local fashion as before. Hence, $\mathbb{T}_{MCC} = \mathbb{T}_{MCC,cel} + \mathbb{T}_{MCC,loc}$. However, in this scenario, for the local stage, consider the behaviour of the average user. We first derive the distribution for all the cloud and then evaluate for the average user. We give a formal definition of this distribution and its proof in the following lemma.

Lemma 4.4 (Multiple clouds cooperation RLNC distribution). *Consider the case of a multiple clouds cooperation scenario that employs RLNC of generation size g and field*

size q . Each cloud is composed of H_n heads from N_{uc} devices with $H_n \leq N_{uc}$. The heads have heterogeneous packet erasure rates ϵ_{jn} , $j \in [1, H_n]$, $n \in [1, C]$ for the links between the source and them. All devices inside each of the C clouds have a homogeneous packet erasure rate ϵ_{loc} for all their $\frac{N(N-1)}{2}$ connection links between them. Then, the distribution for the random number of transmissions required for decoding each cloud is given by $\mathbb{T}_{MCC} = \mathbb{T}_{MCC,cel} + \mathbb{T}_{MCC,loc}$ where each term is given as follows:

$$\mathbb{T}_{MCC,cel} = \max_{n \in [1, C]} \left(\mathbb{T}_U \left(g, q, \prod_{j=1}^{H_n} \epsilon_{jn} \right) \right) \quad (21)$$

$$\mathbb{T}_{MCC,loc} = \begin{cases} \mathbb{T}_B(N_{uc} - H_n, g, q, \epsilon_{loc}), & H_n < N_{uc} \\ \mathbb{T}_B(N_{uc,loc,n}, g_{loc,n}, q, \epsilon_{loc}), & H_n = N_{uc} \end{cases} \quad (22)$$

$$N_{uc,loc,n} = N_{uc} - \left\lfloor P_g \sum_{j=1}^{N_{uc}} (1 - \epsilon_{jn})^g \right\rfloor \quad (23)$$

$$g_{loc,n} = \max_{j \in [1, N_{uc}]} \left(g - \left\lfloor (1 - \epsilon_{jn}) \sum_{i=1}^g p_i \right\rfloor \right) \quad (24)$$

Where in (21) and (22), the parenthesis notation indicates the evaluation of the respective distribution with the given parameters. In (23) and (24), P_g and p_i are respectively the probabilities of linear independence at g transmissions and in each stage of the RLNC Markov Chain. Both are defined in the proof of Lemma 4.1. Also important in the local stage, the number of transmissions depends on the n -th cloud being considered.

Proof. The proof is in the Appendix. \square

With the previous distributions, we simply find a proper operation to observe the behaviour of the system. In our case, we consider the average cloud. To find the trends of the system, we simply evaluate the previous distributions in the homogeneous regime, for example, $\epsilon_{jn} = \epsilon_{cel}$, $\forall j, n$ and $H_n = H_c$, $\forall n$, which makes the average cloud equal to any cloud.

Corollary 4.4.1 (Homogeneous conditions in multiple clouds cooperation). The distribution of multiple clouds cooperation RLNC with homogeneous erasure rates, $\epsilon_{jn} = \epsilon_{cel}$, $\forall j, n$ and $H_n = H_c$, $\forall n$, is the following:

$$\mathbb{T}_{MCC,cel} = \mathbb{T}_B(CH_c, g, q, \epsilon_{cel}) \quad (25)$$

$$\mathbb{T}_{MCC,loc} = \begin{cases} \mathbb{T}_B(N_{uc} - H_c, g, q, \epsilon_{loc}), & H_c < N_{uc} \\ \mathbb{T}_B(N_{uc,loc}, g_{loc}, q, \epsilon_{loc}), & H_c = N_{uc} \end{cases} \quad (26)$$

$$N_{uc,loc} = N_{uc} - \left\lfloor P_g N_{uc} (1 - \epsilon_{cel})^g \right\rfloor \quad (27)$$

$$g_{loc} = g - \left\lfloor (1 - \epsilon_{cel}) \sum_{i=1}^g p_i \right\rfloor \quad (28)$$

Proof. The proof is performed by performing the mentioned evaluations in Equations 21–(24). Moreover, we notice that for the cellular stage, all erasure rates are the same, and the distribution for this stage reduces to employing a similar reasoning as the one in Corollary 4.2.1. \square

5. PERFORMANCE METRICS

With the pmf for each scenario in Section 4, we compute the mean for the number of transmissions, which allows us to compute the throughput and energy. In the cloud cooperation scenarios, the results are relatively equivalent; however, the pmf in both cellular and local stages will depend on the scenario employed as shown in the previous section. Given this, for notation purposes, we omit the difference between \mathbb{T}_{cel} and \mathbb{T}_{loc} in single cloud cooperation and multiple clouds cooperation unless it is a necessary exception.

5.1. Throughput

We define the throughput in the cloud cooperation scenario for a given set of parameters in the following way:

$$R_{CC} = \frac{g}{\max(t_{cel}E[\mathbb{T}_{cel}], t_{loc}E[\mathbb{T}_{loc}])} \quad (29)$$

In (29), t_{cel} and t_{loc} are the durations of a time slot in the cellular and local stages, respectively. The effective rate perceived by a user will be the information sent divided by the completion time multiplied by a cost. For broadcast RLNC, the throughput is $R_B = \frac{g}{t_{cel}E[\mathbb{T}_B]}$.

5.2. Energy consumption

From the energy point of view, we only consider how much energy is required to transmit and receive a packet due to channel erasures. We do not consider the computational energy consumption because they are up to one order of magnitude below the energy expenditure for transmitting and receiving packets for moderate generation (up to 128) and field sizes (up to 2^8) [17], which we employ in our study. We consider that the energy for being idle is the same as for receiving a packet, because we have also observed that they are very close in practice [17].

To compute the energy consumption, we assume that a packet transmission and a packet reception spend the same energy because we observed this for commercial mobile devices in [17]. Then, we consider that the energy cost depends only on the type of connection employed. Therefore, we have two energy costs: E_{cel} for the cellular interface, and E_{loc} for the local interface. Each cost depends on the packet size and the energy per byte. The latter is proportional to the energy per bit for each type of connection. Then, naming the packet size p_s , the energy per byte E_B and the energy per bit E_b for the cellular stage,

we obtain $E_{cel} = p_s E_{B,cel}$ with $E_{B,cel} = 8E_{b,cel}$. Similarly, for the local stage, we obtain $E_{loc} = p_s E_{B,loc}$ with $E_{B,loc} = 8E_{b,loc}$. The energy per bit values are extracted from [28].

For our study, we compute the energy spent for the BS and the average energy spent per device for each transmission scenario. In the following, E_x indicates an energy value, and $E[\cdot]$ is the expected value operator for random variables. The energy expenditure for the BS, E_{BS} , is total number of cellular transmissions necessary before the heads in each cloud can decode the content jointly, multiplied by the energy cost of transmitting a packet on the cellular link. The average energy spent by a device, E_D , is computed from the following: (i) the reception of the heads in the cellular stage; (ii) the transmission of the heads in the local stage; and (iii) the reception of the non-heads in the local stage. The average is computed by dividing the previous total energy by the number of devices.

First, the energy consumption for broadcast is as follows:

$$E_{BS} = E_{cel}E[\mathbb{T}_B], E_D = E_{cel}E[\mathbb{T}_B] \quad (30)$$

Second, the energy expenditure for the single cooperation scenario is shown in (31).

$$\begin{aligned} E_{BS} &= E_{cel}E[\mathbb{T}_{cel}] \\ E_D &= E_{cel} \left(\frac{H}{N} \right) E[\mathbb{T}_{cel}] + E_{loc}E[\mathbb{T}_{loc}] \end{aligned} \quad (31)$$

For the multiple clouds cooperation scenario, the result is equivalent with the number of heads and users per cloud equal to H_c and N_{uc} :

$$\begin{aligned} E_{BS} &= E_{cel}E[\mathbb{T}_{cel}] \\ E_D &= E_{cel} \left(\frac{H_c}{N_{uc}} \right) E[\mathbb{T}_{cel}] + E_{loc}E[\mathbb{T}_{loc}] \end{aligned} \quad (32)$$

5.3. Cellular versus local links

The performance of cooperation will depend on the slot rate and energy use per bit costs on the local and the cellular links. Therefore, we define the r_t as the ratio between cellular and local slot rate costs, and r_e as the ratio between the cellular and local energy cost.

$$r_t = \frac{t_{loc}}{t_{cel}} = \frac{R_{cel}}{R_{loc}} ; r_e = \frac{E_{b,cel}}{E_{b,loc}} \quad (33)$$

5.4. Gain regions

For the analysis with different erasure rates per stage, we define the throughput and energy gains of cloud cooperation against broadcast RLNC from (30) and (31) as shown in (35).

$$\begin{aligned} G_t &= \frac{E[\mathbb{T}_{cel}]}{\max(r_t E[\mathbb{T}_{cel}], E[\mathbb{T}_{loc}])} \\ G_e &= 1 - \frac{r_e \left(\frac{H}{N} \right) E[\mathbb{T}_{cel}] + E[\mathbb{T}_{loc}]}{r_e E[\mathbb{T}_{loc}]} \end{aligned} \quad (34)$$

We define throughput gain as the ratio of the cloud cooperation and broadcast RLNC throughputs. The energy gain of cooperation over broadcast is defined as the saving in energy for the devices, because cooperation always save energy at the BS.

5.5. Optimal cloud size

All the studied scenarios can be regarded as the spectrum of cooperation, where broadcast is the case of no cooperation, single cloud cooperation the case of full cooperation and multiple clouds cooperation the in-between. Then, we define the optimal cloud size as the size that all the clouds should have in order to minimise the total transmission time. We consider this because we have observed that in the case of having the same erasure rate for all the links in the cellular stage and the same erasure rate for all the links in the local stage, employing the same cloud size for all the clouds, two main situations dominate either the cellular or the local transmission time. First, the cellular transmission time mostly depends on the smallest cloud, for example, the one with the least amount of devices. Second, the local transmission time depends on the remaining devices to be served, which is proportional to the biggest cloud. We verify this in the results section and then focus on the homogeneous case because it gives the best performance. For this case, there will be a trade-off for the number of transmissions in each stage. For the broadcast case, we simply consider that $N_{uc} = 1$ and $\mathbb{T}_{MCC,loc} = 0$. Thus, the optimal cloud size is defined as follows:

$$N_{uc}^* = \min_{N_{uc}} \mathbb{T}_{MCC} \quad (35)$$

5.6. Overhead

We calculate the performance of TC against RLNC by reviewing the optimal field choices that minimises an overhead-related cost function and compare them against the performance of both RLNC with $GF(2)$ and $GF(2^8)$ given that they represent opposite extremes.

We define the overhead for a field scheme s and transmission scenario t as

$$\odot_{s,t} = (B + |v|_{s,t})(\mathbb{T}_{s,t} - \mathbb{T}_{s,min,t}) + |v|_{s,t} \mathbb{T}_{s,min,t} \text{ [bits]} \quad (36)$$

In (36), $\odot_{s,t}$ is the overhead viewed as random variable depending on a given scheme and transmission scenario. $|v|_{s,t}$ is the coding coefficients overhead for the given scheme and scenario. $\mathbb{T}_{s,t}$ is the (random) number of transmissions of the given scheme and scenario and $\mathbb{T}_{s,min,t}$ is a

random variable for the minimum amount of transmissions that the scheme might take in the given scenario. A reasonable approximation for this variable is $\mathbb{T}_{GF(2^8),I}$. Given that we are evaluating the overhead, our choice for the cost function to obtain the optimal field scheme is the mean overhead. Then, the optimal field scheme for a given scenario is the one that minimises the following cost function (after rearranging terms):

$$\begin{aligned} \min_{\mathbf{q}} \quad & (B + |\mathbf{v}[\mathbf{q},I]|)E[\mathbb{T}_{\mathbf{q},I}] \\ \text{s.t.} \quad & \mathbf{q}_i = 2^{2^{k_i}}, i \in [1, g], k_i \in \mathbb{Z}^+ \end{aligned} \quad (37)$$

In the nonlinear integer problem defined in (37), we have substituted the scheme subscript to highlight the dependence on the fields of the mean overhead minimisation because the optimal scheme is a particular choice of fields. For a given solution of (37), we evaluate its cost in (36) to review the performance of the given scheme.

6. NUMERICAL RESULTS

We use a set of parameters in the following ranges $1 \leq N \leq 50$, $g = \{64, 128\}$, $q = 2^8$ and $0 \leq \epsilon_{cel} = \epsilon_{loc} = \epsilon \leq 0.6$. The time slot duration is set to $t_{cel} = 0.5$ ms to conform to the LTE-A E-UTRA [29] and its set of D2D specifications. For the energy, we extracted the energy per bit cost from the energy model in [28] and use a packet size N_B of 500 B. For RLNC, in case of increasing the packet size (e.g. 1.5 KB) while keeping the total amount of data, the overhead contribution from the coding coefficients will be low because the amount of bits required to send the coding coefficients will be less than the required packet size, reducing the required signalling. For the case of a low packet size (e.g. 100 B), the overhead due to the coding coefficients per packet increases because it is comparable with or even higher than the packet size. Then, for very low packet sizes, most of the information sent is mainly signalling reducing the throughput. For the overhead of TC, we evaluate broadcast and single cloud cooperation with a set of parameters in the following ranges $N = \{1, 30, 50\}$, $g = \{16, 32, 64, 128\}$, $\epsilon_{cel} = \epsilon_{loc} = \epsilon = \{0.1, 0.3, 0.5\}$. We use a representative wireless network packet size of 1.6 KB ($B = 12\,800$ bits). For the optimal field scheme, we obtain the solutions that minimise the cost function in (37) by performing a search for the solutions in the feasible set of (37) and verifying which minimises the cost function. The considered field sizes for the feasible set were $2, 2^2, 2^4, 2^8, 2^{16}$ and 2^{32} as in [19], because current computer data types can easily represent these values. Following, we make the comparison in percentage value obtained as $E[\mathbb{O}_{s,I}]/gB \times 100\%$.

Figure 4 shows how the throughput varies depending on the ratio of the cellular and local data rate. The ratios are obtained by fixing the cellular data rate and varying the local data rate. When the local data rate is lower than the cellular rate, the cooperative schemes provide lower throughput than the broadcast scheme. Conversely, when

the local data rate is higher than the cellular data rate, the cooperative schemes deliver a higher throughput than broadcast. The throughput is highest when the local links rate are twice as faster as the cellular ones. The number of heads controls how much gain can be obtained and where it occurs for a given ratio. When the number of heads decreases, the throughput also diminishes because there are fewer heads each with an independent chance of receiving the packet.

Figure 5 shows how the energy for the devices changes as the ratio between the cellular and local energy per bit changes. The energy cost in the cellular link is fixed and the cost on the local link is changed to obtain the different ratios; consequently, the energy per bit for broadcast is constant.

When the energy cost for the local links is higher than the cellular energy cost, the cooperation performs worse than broadcast. The extra consumption for cooperation comes from the transmissions in the local stage. Contrarily, when the cost of the local links is lower than the cost of

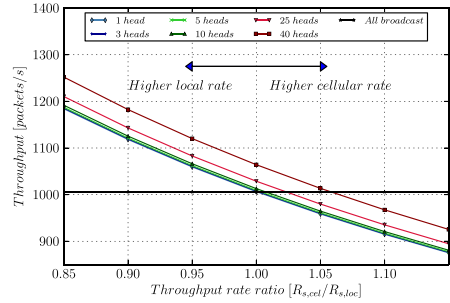


Figure 4. The throughput of broadcast and cooperation with different number of heads, for different ratios between the data rate on the cellular and local link. Used parameters: $g = 64$, $q = 2^8$, $\epsilon = 0.4$, $N = 50$.

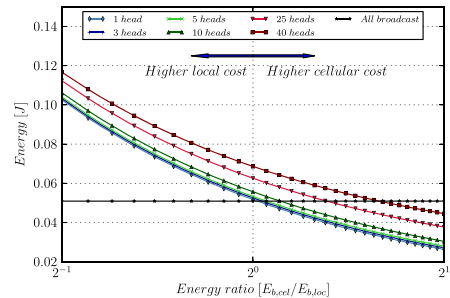


Figure 5. The energy per generation of broadcast and cooperation with different number of heads, for different ratios between the energy per bit on the cellular and local link. Used parameters: $g = 64$, $q = 2^8$, $\epsilon = 0.4$, $N = 50$.

the cellular links, single cooperation uses less energy than broadcast. In these cooperation scenarios, the consumption is determined by the number of heads on the cellular stage.

For a cloud of a determined size, in the case of having the same erasure rate for all the links in the cellular stage, there is a trade-off between throughput and energy expenditure that depends on the number of heads. The higher number of heads, the higher the throughput. When a coded packet is broadcasted to the cloud in the cellular stage, having more heads cooperating with each other rapidly increases the probability that at least one of them obtains it, to later share this knowledge with all the devices. This in turn increments the probability of having all the packets inside the cloud in g transmissions, enhancing the throughput. However, this comes at the expense of higher energy consumption because more energy is spent when receiving the packets to the cloud. For a low amount of heads, the energy expenditure for the devices is low, but the same for the throughput given that more transmission is required because less devices are cooperating. At the end, it is a design decision because both benefits cannot be achieved at the same time.

Figure 6 shows the regions where cooperation provides a gain in terms of throughput for a wide range of erasure rates on the cellular and local links. The lines show where broadcast and cooperation perform the same, for $r_t = [0.5, 0.8, 1, 1.5, 2]$. In the region below each line, cooperation provides higher throughput than broadcast for that particular r_t . Above the line, broadcast performs better. For example, in the case of a fast local link $r_t = 0.5$, then cooperation provides a gain for almost all considered erasure rates, even in cases where the local erasure rate is much higher than the cellular.

Figure 7 shows the regions where cooperation provides a gain in terms of energy saving on the devices for various erasure rates on the cellular and local links. The

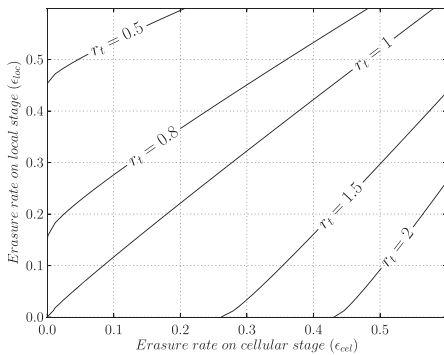


Figure 6. For different values of r_t , the lines indicate where cooperation and broadcast provide the same throughput for various erasure rates on the cellular and local links. Below each line, cooperation performs better for the respective r_t . Used parameters: $g = 128$, $q = 2^8$, $H = 40$, $N = 50$.

lines show where broadcast and cooperation performs the same, for $r_e = [0.5, 0.75, 1, 1.5, 2]$. In the region below each line, cooperation provides a lower energy per bit than broadcast for that particular r_e . Above the line, broadcast performs better.

Figure 8 shows the results for two simulations. The first simulation shows the cellular transmission time for two different scenarios. In the first scenario, for the same losses in the cellular stage, $\epsilon_{cel} = 0.3$, we show the cellular transmission time for two clouds where the first cloud size is fixed to six devices and the second cloud size ranges from one to 20 devices. In the second scenario, for the same losses in the cellular stage, we show the transmission time for five clouds where all the cloud sizes are the same. We vary the size of all these clouds from one to 20 devices.

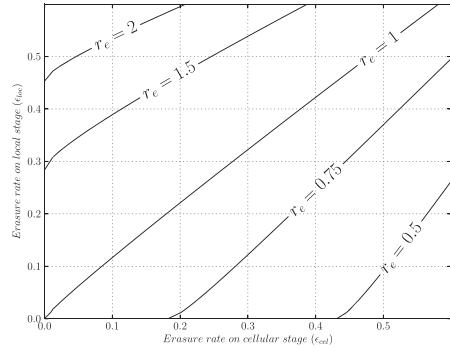


Figure 7. For different values of r_e , the lines indicate where cooperation and broadcast provide the same energy per bit for various erasure rates on the cellular and local links. Below each line, cooperation performs better for the respective r_e . Used parameters: $g = 128$, $q = 2^8$, $H = 40$, $N = 50$.

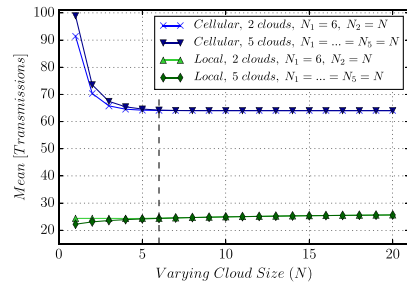


Figure 8. For the cellular transmission time, the smallest cloud dominates the transmissions below the homogeneous size (dashed line). Above it, it remains mostly constant. For the local transmission time, it remains constant below the homogeneous size (dashed line). Above it, the biggest cloud starts to slowly dominate the transmissions. Used parameters: $g = 64$, $q = 2^8$, $\epsilon_{cel} = 0.3$, $\epsilon_{cel} = 0.1$, $H = N$, N varies.

For the first scenario, we observe that as the number of devices in the second clouds is less than six (dashed line), then transmission time in the cellular stage increases given that this cloud requires more transmissions than the first cloud. For the second scenario, as we increase the number of devices in the five clouds, the error between one varying cloud and five varying clouds becomes very small.

The second simulation shows the trends for the local transmission time similarly in two scenarios. In the first scenario, assuming equal losses in the local stage, $\epsilon_{loc} = 0.1$, we present the local transmission time for two clouds keeping fixed the size of the first one to six devices and varying the size of the second from one to 20 devices. In the second scenario, for equal losses in the local stage, we present the local transmission time where all the clouds have the same size, and we vary them from one to 20 devices. Here, for the first scenario, we notice that the local transmission time is higher when second cloud size is bigger than the first one. The reason being that the second cloud becomes the biggest one and dominates the local

transmission time. Similarly, for the second scenario, we observe that the local transmission time matches for both cases after six devices (dashed line).

At the end, we see that the homogeneous is the best case that we could obtain. In any other case, one of the following two situations occurs: (i) the cellular transmission time is high, while the local transmission time is constant, or (ii) the cellular transmission time remains constant, while local transmission time is high. The homogeneous case is simply the boundary between the previous two.

Figure 9 shows the trade-off for the number of users per cloud for different given erasure rate in the cellular and local stages. We clearly observe that there is a cloud size N_{uc} for which the total number of transmissions T_{MCC} is minimum, thus minimising the energy consumption and maximising the throughput.

We study the overhead performance for the three schemes for both scenarios to compare the optimal scheme performance.

6.1. Optimal telescopic codes configuration and performance for broadcast

Figure 10(a) first shows the optimal scheme obtained from solving (37). Second, Figure 10(b) shows the corresponding optimal scheme overhead against the overhead from the other two code schemes. Both results are for 30% losses in all the links of the remote stage. Both the optimal field scheme and overhead are presented versus the combinations of users, N , and generation sizes, g . Each bar in Figure 10(a) indicates the amount of coding coefficients for the given fields as percentages in the generation. For all shown combinations in Figure 10(a), as g increases for a fixed amount of users, most of the coefficients are drawn from $GF(2)$ with a diminishing percentage being chosen from other fields. Nevertheless, for a fixed generation size and increasing number of users, only for low values of g it can be observed a tendency to use more coding coefficients in high fields. Figure 10(b) exhibits the overhead mean of the three schemes. For all the cases, we see that the optimal

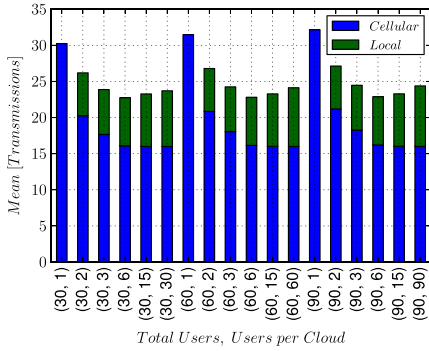
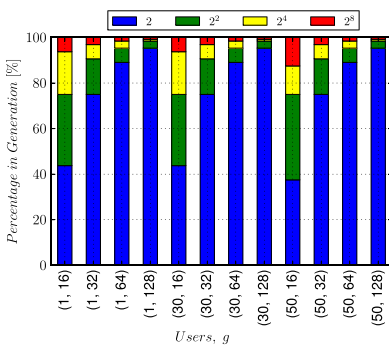
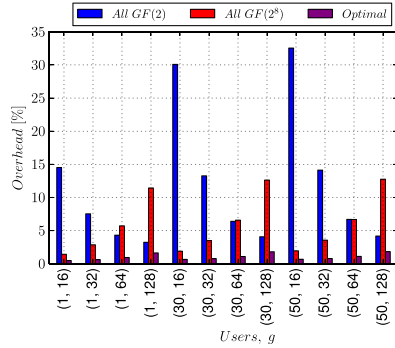


Figure 9. Optimal cloud size for $g = 16$, $q = 2^8$, $\epsilon_{cel} = 0.3$ and $\epsilon_{loc} = 0.1$.



(a) Optimal field scheme, q^*



(b) Overhead mean (%)

Figure 10. Schemes performance for broadcast. $\epsilon = 0.3$.

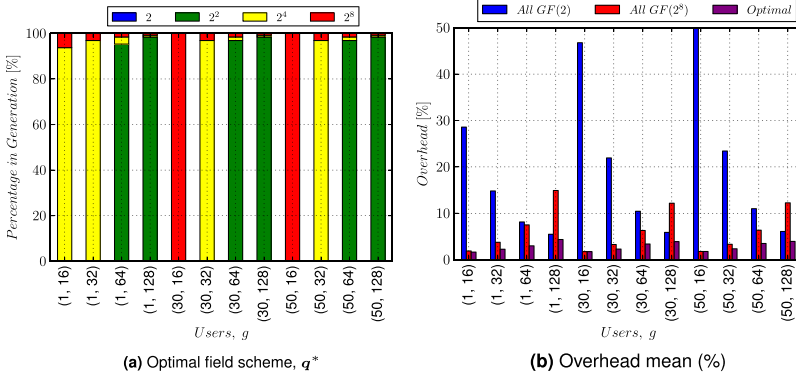
Figure 11. Schemes performance for cloud cooperation. $\epsilon = 0.3$.

Table I. Scenarios and schemes comparison.

Transmission scenario	Code scheme	Overhead	Transmission time			*Energy	*Throughput
			Cellular	Local	Total		
Broadcast	RLNC	Med	High	None	High	Med	Low
	Telescopic	Low	High	None	High	Low	Low
Single cloud cooperation	RLNC	Med	Low	Med	Med	High	Med
	Telescopic	Low	Low	Med	Med	High	Med
Multiple clouds cooperation	RLNC	Med	Low	Low	Low	Med	High
	Telescopic	Low	Low	Low	Low	Low	High

$\epsilon_{cel} = 0.3$, $\epsilon_{loc} = 0.1$, $N = 60$, $H = N$, $r_e \leq 1$, $r_l \geq 1$.
RLNC, random linear network coding.

field scheme outperforms both $GF(2)$ and $GF(2^8)$ achieving a less than 2% total overhead in most of the cases. For $g \leq 32$, increasing the number of receivers greatly affects the total overhead, almost doubling it in the case of $g = 16$. Although, for $g \geq 64$, the overhead is less sensitive to the number of receivers.

6.2. Optimal telescopic codes configuration and performance for single cloud cooperation

Correspondingly, Figure 11 exhibits the performance for cloud cooperation. Figure 11(a) presents the optimal scheme obtained from solving (37) for cloud cooperation and 30% losses for both the remote and local links. In this case, for increasing g and fixed users amount, more than 90% of the coding coefficients belong to a single field. For $g \leq 32$, the scheme distribution goes mostly to either $GF(2^4)$ or $GF(2^8)$. For $g \geq 64$, most of the coefficients are chosen from $GF(2^2)$. For a fixed generation size and varying amount of users, the coding coefficients distribution appreciably changes for $g = 16$ and slightly for $g = 64$. Figure 11(b) displays the overhead mean; the optimal scheme provides a lower mean overhead than both $GF(2)$ and $GF(2^8)$, except for the cases of 30

and 50 receivers with 16 packets as generation size, where the optimal scheme and subsequently mean overhead are the same as $GF(2^8)$. Still, for all the cases, total overhead mean does not exceed 2.5% with some cases being approximately less than 1%.

Finally, in Table I, we present a solution comparison to show our major results. We consider a packet erasure rate of 30% for the cellular links and 10% for the local links. Similarly, we consider a large fixed amount users, $N = 60$, with all of them being heads. Also, the energy cost in the cellular stage is equal or higher as the energy cost in the local stage ($r_e \leq 1$). Similarly, we consider that duration of a time slot in the cellular stage is the same as in the local stage ($r_l \geq 1$). Under this scenario, the multiple clouds cooperation approach provides the best performance in terms of throughput. Thus, we expect the highest gains from cooperation and coding in this regime.

7. CONCLUSIONS

In this work, we presented an in-depth study of the specific operating regions where cooperation provides gains in throughput and energy over coded broadcasting techniques. Our numerical results showed that gains can be achieved even if the long-range and short-range

technologies transmit at comparable data rates or there are few differences in the erasure rates in each stage. More importantly, we showed that cooperation can provide several fold gains broadcast as long as the short-range link is at least twice as fast as the long-range one. Finally, our results showed that a moderate number of heads (e.g. three or more) per cooperative cluster is enough to yield the high throughput gains while maintaining a low energy consumption at the receivers. Also, for multiple clouds cooperation, we observed that the cloud size should be around six nodes in most of the cases.

We also proposed the use of TC for network-coded cooperative to reduce the total system overhead. We review the performance of TC against classical RLNC systems using either $GF(2)$ or $GF(2^8)$ with two common multicast scenarios: broadcast and single cloud cooperation. For a broadcast scenario, we observed that the optimal field scheme always outperforms both traditional RLNC schemes where in some cases total overhead is less than 0.5%. For single cloud cooperation, the total overhead was less than approximately 3% in all the cases. In a single cloud cooperation scenario, the penalty for including coefficients from low fields becomes significant because of the presence of the hops. However, this becomes less critical as the generation size increases.

Future work shall focus on protocol design for cooperative schemes in highly dense scenarios as well as implementation and evaluation of the most promising schemes in Aalborg University's Raspberry Pi testbed [30]. Regarding optimal overhead codes, future work in this area should consider the inclusion of other scenarios such as multiple clouds cooperation and multihops.

APPENDIX

Proof of Lemma 4.1

Let $\mathbb{T}_{TC,i}$ be a random variable for the number of transmissions needed to receive an l.i. coded packet in a stage of the Markov Chain for TC in Figure 3. This is a geometric distribution[†] with success probability given by $p_i = 1 - q_i^{-g+(i-1)}$, $i \in [1, g]$. In general, $q_i = 2^{k_i}$, $k_i \in \mathbb{Z}^+$. Later, the distribution for TC is given as follows:

$$\mathbb{T}_{TC} = \sum_{i=1}^g \mathbb{T}_{TC,i} \quad (\text{A.1})$$

A direct computation of (A.1) is analytically intractable due to the requirement of computing $g-1$ discrete convolutions. Nevertheless, in the pgf domain, this operation turns into a product making the analysis fairly easier.

First, let us define the pgf of a discrete random variable \mathbb{T} from its pmf as $G_{\mathbb{T}}(z) = E[z^{\mathbb{T}}] = \sum_{t=-\infty}^{\infty} \Pr[\mathbb{T} = t] z^t$

[†]We use the definition of the geometric distribution that accounts for the random number \mathbb{T} of Bernoulli trials of success probability p required to obtain the first success. Later, if $\mathbb{T} \sim \text{Geom}(p) \implies \Pr[\mathbb{T} = t] = (1-p)^{t-1}p$, $t \in [1, \infty)$

$t]z^t = \sum_{t=-\infty}^{\infty} f_{\mathbb{T}}(t)z^t$. Second, the bilateral Z-transform of the pmf as $F(z) = \mathcal{Z}\{\Pr[\mathbb{T} = t]\} = \sum_{t=-\infty}^{\infty} \Pr[\mathbb{T} = t] z^t = \sum_{t=-\infty}^{\infty} f_{\mathbb{T}}(t)z^t$. Doing little algebra with the previous two definitions, it can be seen that $F(z) = G_{\mathbb{T}}(z^{-1})$. Thus, the Z-transform of (A.1) becomes

$$F_{\mathbb{T}_{TC}}(z) = \prod_{i=1}^g G_{\mathbb{T}_{TC,i}}(z^{-1}) \quad (\text{A.2})$$

Calculating the pgf of $\mathbb{T}_{TC,i}$ with the previous definitions and inserting in (A.2), we obtain the following:

$$\begin{aligned} F_{\mathbb{T}_{TC}}(z) &= G_{\mathbb{T}_{TC}}(z^{-1}) \\ &= \prod_{i=1}^g \frac{p_i z^{-1}}{1 - (1-p_i)z^{-1}}, \quad |z| > \max(1-p_i) \end{aligned} \quad (\text{A.3})$$

In (A.3), we notice $\prod_{i=1}^g p_i$ is simply the probability of decoding in exactly g transmissions, $\Pr[\mathbb{T}_{TC} = g]$, which we relabel as P_g . Also, $\gamma_i = 1 - p_i$ is probability of obtaining an l.d. in stage i . Including this (A.3), we obtain

$$F_{\mathbb{T}_{TC}}(z) = P_g z^{-g} \prod_{i=1}^g \frac{1}{1 - \gamma_i z^{-1}}, \quad |z| > \max(\gamma_i) \quad (\text{A.4})$$

From (A.4), we analytically observe the following: First, as expected, the pmf will be a right handed, causal and stable sequence from the signal processing perspective. The reason being that the pmf Z-transform Region of Convergence includes $|z| = \infty$ and $|z| = 1$ because $\max(\gamma_i) < 1$ always. Also, the pmf sequence will begin at g because of the delay term z^{-g} , which makes reference to the fact that g transmissions are required to receive g l.i. packets.

At this point, we make the following observation: Depending on the field distribution considered, at least some of the l.d. probabilities may be equivalent to each other. Thus, in general, the Z-transform of the TC, (A.4), may have repeated roots in its pgf. Therefore, let us consider that we have γ_l , $l \in [1, L]$ distinct l.d. probabilities in the Markov Chain in Figure 3, each repeated m_l times with $\sum_{l=1}^L m_l = g$. Then, (A.4) becomes (A.5):

$$F_{\mathbb{T}_{TC}}(z) = P_g z^{-g} \prod_{l=1}^L \frac{1}{(1 - \gamma_l z^{-1})^{m_l}}, \quad |z| > \max(\gamma_l) \quad (\text{A.5})$$

Afterwards, we perform a partial fraction expansion on the product term in (A.5), which is rational, which turns it into

$$F_{\mathbb{T}_{TC}}(z) = P_g z^{-g} \sum_{l=1}^L \sum_{n=1}^{m_l} \frac{a_{l,n}}{(1 - \gamma_l z^{-1})^n}, \quad |z| > \gamma_{l_{\max}} \quad (\text{A.6})$$

In (A.6), we have splitted the product as a sum of the contributions of each of its poles of the Z-transform in (A.6). Here, RLNC appears as a special subcase due to the

linear dependence probabilities being unique in that case. Hence, we can obtain the pmf for RLNC as a subcase of the for TC.

From (A.6), the $a_{l,n}$ coefficients $a_{l,n}$, $l \in [1, L]$, $n \in [1, m_l]$ are the residues of the complex function $\left[\prod_{m=1}^L (1 - \gamma_m z^{-m_l}) \right]^{-1}$ at the poles $z = \gamma_l$, $l \in [1, L]$. These residues are calculated using the expression:

$$a_{l,n} = \lim_{z \rightarrow \gamma_l} \frac{d^{m_l-n}}{dz^{m_l-n}} \left(\frac{G_{\text{TC}}(z^{-1})(1 - \gamma_l z^{-1})^{m_l}}{P_g z^{-g}} \right) \quad (\text{A.7})$$

Performing this evaluation and doing inverse Z-transform algebra, the one obtains (6), which concludes the proof.

Proof of Corollary 4.1.1 The proof comes by letting $q_i = q \forall i \in [1, g]$, which gives different unique i.d. probabilities in the Markov Chain, which in turns gives all simple poles (A.4). This makes quite easy to evaluate the residues as $a_i = \lim_{z \rightarrow \gamma_i} \left[\prod_{m=1}^g (1 - \gamma_m z^{-1}) \right]^{-1} \times [(1 - \gamma_i z^{-1})]$ and noting that the relationship $\gamma_m \gamma_i^{-1} = q^{m-i}$ between the i.d. probabilities giving the result in (8), and this concludes the proof.

Proof of Lemma 4.2 For the probability of the maximum number of transmissions of the worst receiver to be less than or equal to t transmissions, then necessarily all other receivers must also have this (or in general less) transmissions than the worst receiver.

Therefore, under the packet erasures independence assumption, we can compute the cumulative density function (CDF) for broadcast with TC, as $F_{\text{TB}}(t) = \Pr[\text{TB} \leq t] = \prod_{j=1}^N \Pr[\text{TB}_j \leq t]$ with $\Pr[\text{TB}_j \leq t]$ being the CDF obtained from the pmf in (10) with the resulting CDF in (A.8).

$$F_{\text{TB}}(t; N, g, \mathbf{q}, \epsilon_1, \dots, \epsilon_N) = \prod_{j=1}^N \left(\sum_{k=g}^t \sum_{i=g}^k \binom{k-1}{i-1} (1 - \epsilon_j)^i \epsilon_j^{k-i} f_{\text{TC}}(i; g, \mathbf{q}) \right) \quad (\text{A.8})$$

Finally, to obtain the pmf for broadcast, we simply compute $f_{\text{TB}}(t) = F_{\text{TB}}(t) - F_{\text{TB}}(t-1)$, which gives (11).

Proof of Lemma 4.3 In the cellular stage, each coded packet is acknowledged as received if at least one head obtains it, regardless if it is l.i. or not. This event occurs with probability $1 - \prod_{j=1}^H \epsilon_j$ because all links need to fail for a packet to not be received. Therefore, the distribution of the number of transmissions to obtain a coded packet is $\text{Geom}(1 - \prod_{j=1}^H \epsilon_j)$. Because we need to account for g packets, the distribution for receiving all the packets without considering the coding scheme is $\text{NB}(g, 1 - \prod_{j=1}^H \epsilon_j)$ given that it is the sum of g geometric distributions. Later, we couple the resulting pmf with the coding scheme one by following the same procedure as in the proof of Lemma 4.1 to obtain (10). Doing the calculations, we obtain (13).

In the local stage, the heads take turns to broadcast their content between all devices in the cloud. Given that we

have assumed coordination among the heads, any temporal transmitting head behaves as a source broadcasting recoded packets. Then, the pmf for this stage is a particular case of (12).

At this point, we differentiate two cases: not all heads and all heads. For the former, we make the approximation that the non-heads will become the dominant factor in the broadcast pmf, given that they have no collected packets from the previous stage. In case of the latter, there is no dominant set of devices with a particular number of packets. So, in general, we need to exclude from the total amount of devices, N , the devices that may have finished before (although depending on the conditions this number might be very low) and account that some devices have some packets already.

To obtain an average number of devices that may have finished in the cellular stage for the all heads case, N_f , we approximate it as the mean for the random number of devices that have g l.i. packets after exactly g transmissions have occurred. We round down this to provide an integer result, so $N_f = \lfloor E[\text{N}_f] \rfloor$. Assuming that g transmissions occur in the cellular stage is reasonable because the mean of the distribution in (13) is $g/(1 - \prod_{j=1}^N \epsilon_j)$. This mean tends to g rapidly for practical values of the ϵ_j and N .

To calculate the distribution of the devices that have finished, N_f , we notice that each device meeting the previous condition can be regarded as a Bernoulli trial with success probability $P_g(1 - \epsilon_j)^g$ because all packets must be received and l.i. for each device independently. So, we consider $\text{N}_f = \sum_{j=1}^N \text{Bernoulli}(P_g(1 - \epsilon_j)^g)$ and taking the mean to this expression gives $E[\text{N}_f] = \sum_{j=1}^N E[\text{Bernoulli}(P_g(1 - \epsilon_j)^g)] = P_g \sum_{j=1}^N (1 - \epsilon_j)^g$. Later, $N_f = \lfloor E[\text{N}_f] \rfloor = \lfloor P_g \sum_{j=1}^N (1 - \epsilon_j)^g \rfloor$ from which we obtain $N_{\text{loc}} = N - N_f$, which gives (15).

To obtain how many packets we need to transmit in the local stage, we calculate how many packets does each device j , $j \in [1, N]$ has on average after g transmission have occurred rounded down, $\lfloor E[\text{G}_j] \rfloor$. Then, we will transmit as many coded packets as required to ensure that the device that has the less number of packets from the cellular stage acquires the whole generation, for example, $g_{\text{loc}} = \max_j(g - \lfloor E[\text{G}_j] \rfloor)$.

For the j -th device, in g transmissions, it will have received G_j l.i. packets. The i -th transmission with $i \in [1, g]$ can be regarded as a Bernoulli trial that has success probability $p_i(1 - \epsilon_j)$. Thus, $\text{G}_j = \sum_{i=1}^g \text{Bernoulli}(p_i(1 - \epsilon_j))$ for which its mean is $(1 - \epsilon_j) \sum_{i=1}^g p_i$. Then, doing the remaining algebra, we obtain (16), and this concludes the proof.

Proof of Lemma 4.4 This proof is similar as the preceding one, but some differences occur. First, instead of broadcasting to a single cloud in the cellular stage, we broadcast to $1 < n < C$ clouds, so the number of transmissions will be upper bounded by the worst cloud, hence the computation as described in (21). Second, in the local stage, we calculate the new parameters for

evaluating the distributions in each cloud depending on the cloud being considered in general because the parameters depend on the erasure rates of cellular stage. Nevertheless, the results from the proof of Lemma 4.3 still hold.

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Paper B.

Paper C

Getting Kodo: Network Coding for the ns-3 Simulator

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ABSTRACT

Network Coding (NC) has been shown to improve current and upcoming communication systems in terms of throughput, energy consumption and delay reduction. However, today's evaluations on network coding solutions rely on home-grown simulators that might not accurately model realistic systems. In this work, we present for the first time the steps to use Kodo, a C++11 network coding library into the ns-3 simulator and show its potential with basic examples. Our purpose is to allow ns-3 users to use a flexible and reliable set of network coding functionalities together with the technologies simulated in ns-3. Therefore, in this paper we (i) show how to set up the Kodo library with ns-3, (ii) present the underlying design of the library examples, and (iii) verify the performance of key examples with known theoretical results.

CCS Concepts

•Networks → Network simulations; *Packet-switching networks*; •Mathematics of computing → Coding theory; •Computing methodologies → Simulation tools; •Software and its engineering → Software libraries and repositories;

Keywords

Network Coding, C++, ns-3, simulator

1. INTRODUCTION

Since its inception, network coding [14] has been a disruptive technology that allows intermediate network nodes to combine packets, instead of just routing them, resulting in increased throughput, reliability, and lower delay. NC implementations have also corroborated these promised gains

under specific scenarios [15, 23, 24, 27, 29, 30].

In most previous implementations, the Kodo C++11 network coding library [31] was used. Kodo is intended to make network coding implementations available to both researchers and commercial entities, in particular those developing protocols. Kodo provides fast implementations of finite field arithmetics and the encoding, decoding and re-coding functionalities for a variety of network codes, including Random Linear Network Coding (RLNC) [22], Perpetual [21] and Fulcrum network codes [28]. The library is continuously tested to support a large number of operating systems, compilers and architectures with hardware acceleration (SIMD) [6]. Hence, Kodo has been designed to ensure performance, testability and flexibility.

An important part of the evaluation process for these protocols is the simulation stage that aids developers to verify analytical results, rethink the modeling process by including unobserved system effects or proceed with a given design. Through the research community, the ns-3 project [8] aims to develop and establish an open network simulation environment for research. Among the project's goals are: simulation of standard technologies, simple usage and debugging, code testing and documentation that caters to the needs of the simulation workflow. Although there has been various initiatives to develop simulations tools in the network coding environment, [1, 9, 12, 18], most of these simulators: (i) may not be continuously maintained and tested, (ii) may rely on former functionalities of its components and (iii) are hard to integrate with standard technologies. Thus, to date there are no accurate network coding libraries that are well-tested and maintained to interact with deployable network simulation environments. Hence, in this work we provide for the first time, a set of examples compliant with ns-3 using Kodo as an external library for network coding where we verify know and expected results from the NC literature.

Our work is organized in the following way: Section 2 provides the theoretical aspects regarding the encoding, decoding and recoding of RLNC packets indicating some application scenarios. Section 3 shows how to get the Kodo library for ns-3 in an easy and rapid fashion. Section 4 describes the design and implementation details of our examples. Section 5 provides known verifiable results in the NC literature using several ns-3 simulations to validate the examples. Final conclusions of our work are drawn in Section 6.

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2. NETWORK CODING BASICS

Kodo implements core functionalities of intra-session NC (i.e., where data packets from a single flow are combined with each other). In this type of network coding, the original data $P_j, j \in [1, g]$, each of B bits, is used to create coded packets. In the following subsections, we describe the basic functionalities of RLNC [22], namely encoding, decoding and recoding. Later, we mention applications that could potentially benefit from including RLNC as a coding scheme. More complex code variants available in Kodo are described in more detail in [3].

2.1 Encoding

With RLNC, each coded packet is a random linear combination of the original set of packets. Hence, a linearly independent (l.i.) set of g coded packets, $C_i, i \in [1, g]$ is required in order to get the original information. Each original packet is considered as a concatenation of elements from a Galois Field (GF) of a given size q , which we denote $GF(q)$. To create a coded packet, a coding coefficient $v_{i,j}$, is chosen at random from $GF(q)$ for every packet P_j and multiplied and added following the respective GF arithmetics. In this way, a coded packet is:

$$C_i = \bigoplus_{j=1}^g v_{i,j} \otimes P_j, \forall i \in [1, g] \quad (1)$$

To indicate which packets were used to generate a coded packet, one form is to append its coding coefficients. In this case, the overhead included for $C_i, \forall i \in [1, g]$ by the coding coefficients is given by:

$$|v_i| = \sum_{j=1}^g |v_{i,j}| = g \times \lceil \log_2(q) \rceil \text{ [bits]} \quad (2)$$

2.2 Decoding

To perform decoding, we define $\mathbf{C} = [C_1 \dots C_g]^T$ and $\mathbf{P} = [P_1 \dots P_g]^T$. Then, decoding reduces to solve the linear system $\mathbf{C} = \mathbf{V} \cdot \mathbf{P}$ using Gaussian elimination [19]. Here, the coding matrix \mathbf{V} contains any set of g linearly independent packets C_i as rows as follows:

$$\mathbf{V} = \begin{bmatrix} v_{1,1} \\ \vdots \\ v_{g,1} \end{bmatrix} = \begin{bmatrix} v_{1,1} & \dots & v_{1,g} \\ \vdots & \ddots & \vdots \\ v_{g,1} & \dots & v_{g,g} \end{bmatrix} \quad (3)$$

The decoder begins to compute and remove the contributions from each of the pivot elements, e.g. leftmost elements in the main diagonal of (3), to reduce \mathbf{V} to reduced echelon form. In this way, it is possible to recover the original set of packets.

2.3 Recoding

Network coding allows intermediate nodes in a network to recombine (or recode) packets from their sources whether they are coded or not. In general, a recoded packet should be indistinguishable from a coded one. Thus, we define a recoded packet as R_i and its corresponding encoding vector

as w_i with coding coefficients $[w_{i,1} \dots w_{i,g}]$, as follows:

$$R_i = \bigoplus_{j=1}^g w_{i,j} \otimes C_j, \forall i \in [1, g] \quad (4)$$

$$(5)$$

In (4), $w_{i,j}$ is the coding coefficient that multiplies C_j , uniformly and randomly chosen from $GF(q)$. Any decoder that collects $R_i, i \in [1, g]$ linearly independent coded packets, with their respective w_i , will be able to decode the data as mentioned before.

2.4 Network Coding Applications

There are numerous situations where NC provides benefits over conventional routing schemes. Basic gain descriptions and practical use cases for network coding can be found in [19, Sections 3.4] covering various areas. Among different benefits for communications, network coding can achieve the capacity for networks with multicast flows [26], improve content distribution in peer-to-peer networks [20] or enhance throughput in conventional Transmission Control Protocol (TCP) protocols for reliable communication [25]. For distributed storage systems, network coding has found applications in scenarios where it could incur less redundancy for data protection than simple replication [16].

3. GETTING KODO FOR NS-3

In this section, we explain how to get the Kodo up and running. The procedure helps to quickly add new coding functionalities in ns-3. The project with the examples is available in [4] under a GPLv2 license and it tracks the latest stable revision of the ns-3 development repository, **ns-3-dev**, to get the most recent changes. For research purposes, Kodo uses a free research license detailed in [10].

A more detailed setup guide can also be found at [4]. A descriptive tutorial for the project is available at [5]. We strongly encourage any developer to follow the setup guide. As a reference for this guide, we assume that the ns-3 project is in the `~/ns-3-dev` folder on the developer's system.

1. To get access to Kodo, it is necessary to submit a request at [11] for a research license.
2. Build the local ns-3 repository with its examples since the Kodo examples need the ns-3 binaries in order to build itself. Execute in the local **ns-3-dev** folder:
 - (a) `python waf configure --enable_examples`
 - (b) `python waf build`
3. Go to `~` and clone the **kodo-ns3-examples** git repository. At this point, a confirmed license is necessary to get the Kodo dependencies.
4. Go to the new **kodo-ns3-examples** folder and configure with `python waf configure` (Kodo also uses the **waf** [13] build system) to set and compile the project and its dependencies.
5. Build the **kodo-ns3-examples** and install all the needed files for ns-3 in the `~/ns-3-dev/examples/kodo` folder with `python waf build install --ns3_path="PATH"`. In this case, "PATH" would be `~/ns-3-dev`.

6. Get back to ns-3 folder and build the local ns-3 project with `python waf build`. At this point, the examples should be available to run as any ns-3 simulation.

4. KODO EXAMPLES FOR NS-3

In this section we describe our design implementation and criteria for creating the examples, an overview of what do the examples simulate and the design of two helpers that provide the coding operations for the system represented in the examples. The helpers function is to serve as an interface between ns-3 and the Kodo C++ bindings [2]. These are high level wrappers for the core functionalities of Kodo.

4.1 Examples Implementation

To create our examples, we consider an approach where we perform intra-session network coding, between the application and transport layer of the User Datagram Protocol (UDP) / Internet Protocol (IP) model as shown in Fig. 1. Although other approaches apply coding between the transport and Medium Access Control (MAC) layer [15,24,27,32], we implement it below the application layer to not alter other layers within the protocol stack and keep the implementation simple.

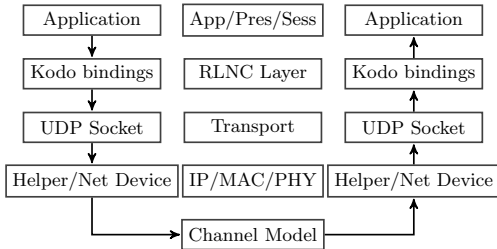


Figure 1: ns-3 + Kodo Implementation Protocol Stack based in a simple UDP/IP model.

In Fig. 1, we consider an application that generates a batch of g packets of some content. For practical reasons, we consider Hyper Text Transfer Protocol (HTTP) traffic and represent it by sending RLNC coded packets through port 80 of a UDP socket from the `UdpSocketFactory`. To encode, recode (if necessary) and decode NC packets, we employ the Application Programming Interface (API) provided by the bindings. We employ UDP datagrams because we consider best effort traffic. For the IP layer, we employ IPv4. For address assignment and routing tables, we use the `InternetStackHelper`, the `Ipv4AddressHelper` and the `Ipv4GlobalRoutingHelper` from ns-3. The details of the MAC, Physical Layer (PHY) and channel models depend on the considered example as we will see.

4.2 Examples Description

With a defined protocol stack, we describe the networks implemented in the examples to evaluate NC performance providing the details for the layers not described previously.

4.2.1 kodo-wifi-broadcast

This example, shown in Fig. 2, simulates a source broadcasting a generation of RLNC packets with generation size

g and field size q to N sinks with an IEEE 802.11b WiFi ad-hoc channel. For the MAC we regard it without Quality of Service (QoS) implemented through `NqosWifiMacHelper`. We pick a WiFi MAC without QoS since in principle we are simulating connectionless best-effort traffic. Thus, the ns-3 net devices are constructed through the `WifiHelper`. Also, we turn off unnecessary MAC parameters, namely: frame fragmentation for frames larger than 2200 bytes and RTS / CTS frame collision protocol for the less than 2200 bytes. Although not required within the example, these parameters need to be included in order for the WiFi MAC to work.

For the PHY of this example, we use the `YansWifiPhyHelper`. The considered PHY includes a channel model that accounts for channel delay, path loss and receiver signal strength in dBm. We employ the `FixedRssLossModel` where the receiver signal (`rss`) is set to a fixed value. We set the broadcast data rate to be the same as unicast for the given `phyMode`. As a transmission policy, the sender keeps transmitting coded packets until all the receivers have g l.i. coded packets, even if some receivers are able to decode the whole generation.

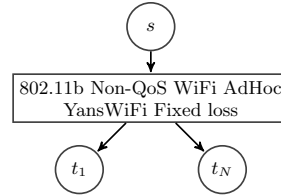


Figure 2: kodo-wifi-broadcast example network.

4.2.2 kodo-wired-broadcast

The example shown in Fig. 3, is similar as in Fig. 2 but instead, we evaluate a basic time-slotted wired system where a node either transmits or receives a single packet in a given time slot with the aid of the `PointToPointHelper`. To model a network with erasures, we consider the `RateErrorModel` for the PHY and channel model. In this case, packets sent from the transmitter could be lost or useless before arriving at the receiver. To control the amount of losses, an `ErrorRate` attribute is included at the `ReceiveErrorModel` attribute of the `RateErrorModel` to indicate the frequency of erasures within a given channel. The resulting topology is a basic representation for packet erasure networks which is akin for network coding applications. The transmission policy is the same as before. For simplicity, all devices are assumed to have the packet erasure rate, $0 \leq \epsilon < 1$. The erasure rate can be introduced as a command-line argument to set the `ErrorRate` attribute from the wired topology as we will see.

4.2.3 kodo-recoders

This example shows the gain of RLNC with recoding in a 2-hop line wired network consisting of a source, N recoders and a sink with different erasure rates. All the links between the sender and the recoders have the same packet erasure rate, $0 \leq \epsilon_{S \rightarrow R} < 1$. Equivalently, the packet erasure rate for the links between the recoders and the receivers is the

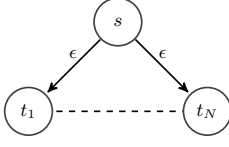


Figure 3: kodo-wired-broadcast example network.

same, $0 \leq \epsilon_{R \rightarrow D} < 1$. Again, both recoding and the erasure rates can be modified by command-line parsing. The transmission policy for this case, is as follows: First, packets are sent to each of the recoders. The transmitter stops if the decoder or all the recoders are full rank, e.g. have g l.i. coded packets. Second, a recoder retransmits packets in another scheduled time slot if l.i. packets to transmit and it stops only if the decoder is full rank.

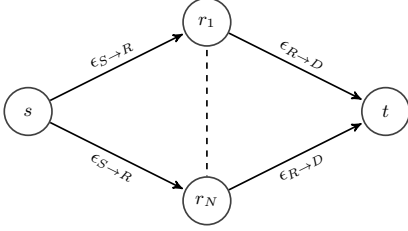


Figure 4: kodo-recoders example network.

4.3 Simulation Workflow and Helpers

In Fig. 5, we show the workflow of the example's simulation source program. This workflow is standard for ns-3 simulations and consists in defining the network (nodes, net-devices) with ns-3 helpers according the required layer functionality described in Section 4.1. Once the socket connections are defined, we call the topology helper which provides the application and coding layers. A receive callback is set to trigger an action whenever a packet is received in a decoder socket. When an encoding or decoding action has been performed, a new event is scheduled through the `ns3::Simulator` class. Events are scheduled until a generation originated in the source is decoded by the sink(s) in the evaluated example.

At the core of each example implementation resides a topology helper which contains all the encoding, recoding and decoding parameters and functionalities of the RLNC layer, the transmission policy and eases the socket connections made in each source file. The helpers are classes that serve as interfaces between the bindings and ns-3. To accomplish this, the helpers are included in ns-3, but its basic elements are objects from the Kodo C++ bindings. For our case, we use two helpers. For `kodo-wifi-broadcast` and `kodo-wired-broadcast`, we use the `Broadcast` topology helper. For the `kodo-recoders` example, we utilize the `Recoders` topology helper. In this section we present the API of these helpers in order to show the interface between Kodo and ns-3. To do so, we elaborate an Unified Modeling

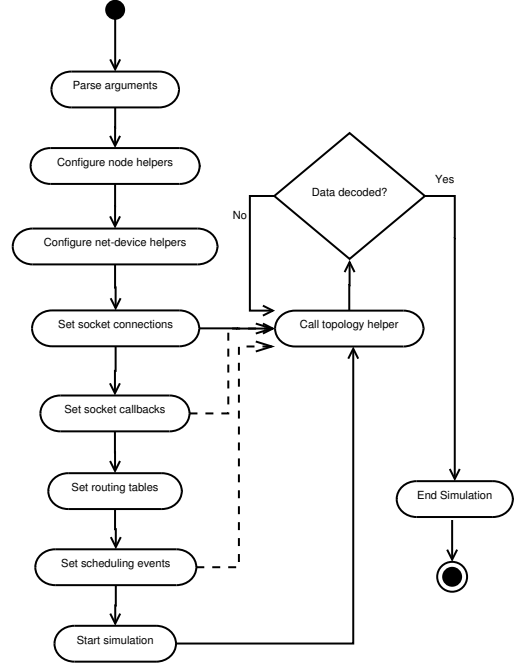


Figure 5: Examples Simulations workflow.

Language (UML) class diagram to visualize the relationships between our bindings and the helpers. We make this review only for the `Broadcast` topology helper, since the analysis for the `Recoders` topology would be similar.

Fig. 6 shows the UML class diagram for the `Broadcast` topology. We have indicated the most important classes that have a type of dependency with the bindings. Also, we employ the UML package notation to indicate the namespace where all the bindings reside. We describe the topology members where the links with `kodocpp` occur. Later, we give an overview of other members whose type are natively contained in the C++ standard library or ns-3. We list the members with dependency on `kodocpp` according to their functionality.

4.3.1 Code Parameter Members

First, `m_codeType` stands for the type of erasure correcting codes utilized. In our implementation, an instance of `kodocpp::codec` is passed to the source program. The available codecs in the bindings are: `full_vector`, `on_the_fly`, `sliding_window`, `sparse_full_vector`, `seed`, `sparse_seed`, `perpetual`, `fulcrum` and `reed_solomon`. A complete description of each codec can be found in the overview section of the Kodo documentation [3]. Second, `m_field` indicates the finite field of the coding scheme. An instance of `kodocpp::field` is passed to the source program. For the available fields: `binary`, `binary4` and `binary8` represent $GF(2)$, $GF(2^4)$ and $GF(2^8)$ respectively.

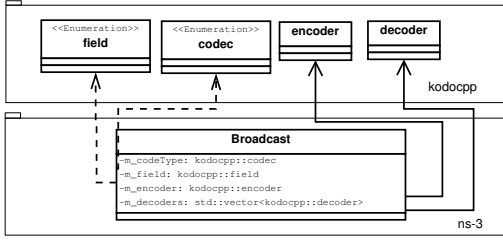


Figure 6: UML class diagram for the Broadcast topology helper interface.

4.3.2 Encoder / Decoder Object Members

The encoder data type is `kodocpp::encoder`, which is provided by the bindings. However, the encoder is not aware of the topology on its own, thus the uni-directional association link to indicate this in Fig. 6. The encoder class is a child class of the more general `kodocpp::coder` abstract class. In this way, the encoder class contains both own and general functionalities, inherited from `kodocpp::coder`, to configure its basic parameters and generate coded data. Similarly, we employ `std::vector<kodocpp::decoder>` to get a local decoder instance for each sink socket. As before, it contains functionalities to configure itself, read coded data and signal when to stop transmissions.

4.3.3 Sockets and Transmission-State Members

For packet transmissions and receptions, we use the native `ns3::Ptr<ns3::Socket>` class. Only the policies for packet transmissions/receptions are implemented through the methods `SendPacket` and `ReceivePacket`. Both of them receive the intended socket for transmission or reception. In case of the transmitter, the packet interval time (`ns3::Time pktTime`) is also given because this will indicate the transmitter the scheduling time for next transmissions. Finally, other members like the number of users to serve, generation, packet sizes and storage buffers are considered too as standard types.

5. SIMULATIONS

To verify the accuracy of the results provided by the examples, we execute a set of ns-3 simulations to observe the behavior of RLNC in well-known scenarios. For the simulations, we compute the distribution of the number of transmissions required to decode a set of g packets with RLNC.

We only consider this metric since, typically, the time cost for the encoding and decoding operations is much lower when compared to the time spent in conveying the information from a transmitter to a receiver. Still, information regarding encoding and decoding speeds for RLNC can be easily obtained by running the benchmarks in [7] for a given platform. Similar benchmarks exist for other codes as well in their respective repositories. In our scenarios, we consider that an ideal feedback scheme is employed, where the source is aware when any destination has acknowledged all its required coded packets. To get this information, we simply call the bindings API required functions in the topology helpers.

We obtain the distribution in two scenarios. First, we

consider the case of one transmitter-receiver pair. Second, we review the scenario of single-hop broadcast for N receivers. We examine these scenarios under two conditions, without packet erasures and with packet erasures. Hence, for the broadcast case, we regard the packet erasure distribution of receiver $j \in [1, N]$ as $Bernoulli(1 - \epsilon_j)$ where ϵ_j is the packet erasure probability. For evaluation purposes, we compute the distribution under a homogeneous packet erasure for all the receivers, $\epsilon_j = \epsilon \forall j$.

To accomplish this, we run the `kodo-wired-broadcast` example and get the number of transmissions required to decode the data in 10^4 runs. To get independent runs, the pseudo-random number generator is set to use the default seed and the `RngRun` parameter is changed in the `RngSeedManager` class by command line parsing.

For the single transmitter and receiver, we use the following parameters: `users = 1`, `generationSize = 30`, `errorRate = 0, 0.1`, and `field = binary, binary8`. For the broadcast case, we evaluate with `users = 10`, `generationSize = 50`, `errorRate = 0.1, 0.2`, and `field = binary, binary8`. To verify our simulations, we compare the practical results with analytical ones. To do so, we compute the Probability Mass Function (pmf) as [33, Eqs. 11-12] for the single receiver and [17, Eq. 3, Sec. III-B] for the broadcast case. Then, we plot the pmf of the analytical distributions against the simulation results.

5.1 RLNC Probability Mass Function

Fig. 7 shows the result for the pmf of the single receiver for the evaluated parameters. We present the results for $g = 30$, $\epsilon = [0, 0.1]$ with $GF(2)$ and $GF(2^8)$ to observe the effect of linear independence in packets transmissions. We also evaluate the consequences of packet erasures in the number of transmissions required for decoding. In all the results, it can be clearly seen that the analytical calculations matches the simulations obtained from ns-3. For the case of no erasures, employing RLNC with $GF(2)$ requires more transmissions compared with $GF(2^8)$ since the possibilities for selecting the coding coefficients are much reduced for the last packets. For the erasure case, the transmissions also increase given that packets might be lost regardless of linear dependency, but still are less than when employing a higher field size.

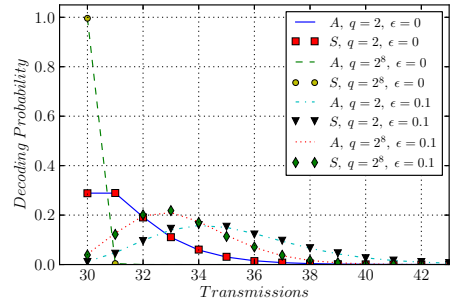


Figure 7: Analytical (A) vs. Simulation (S) for Uni-cast with 1 receiver and 30 packets.

5.2 RLNC Broadcast Probability Mass Function

Fig. 8 shows the result for the pmf of broadcast with RLNC for the case of 10 receivers and the evaluated parameters. In this scenario, $g = 50$. The selected fields are $GF(2)$ and $GF(2^8)$. We present the results for two erasure rates in all the links, $\epsilon = [0.1, 0.2]$.

Again, we observe the theoretical computations fit the simulations results. A difference that can be noticed with the single receiver case is the number of transmissions required to decode increases much more. Excluding the field and the erasure effects, the difference arises from all the receivers being required to get g l.i. coded packets in order to be able to decode. This is the main reason why the pmfs do not start to show a significant non-zero probability of decoding at g transmissions and shortly afterwards.

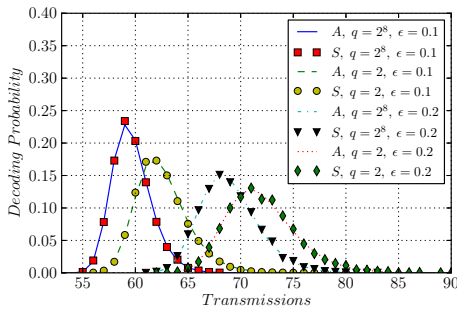


Figure 8: Analytical (A) vs. Simulation (S) for Broadcast with 10 receivers and 50 packets.

6. CONCLUSIONS

Given the increasing amount of NC applications from both academia and industry, we introduced a framework for using the Kodo library with ns-3. We hope that our contribution helps to cover the need for NC simulation capabilities in ns-3. With a set of examples where NC provides known gains, we show that our library complies with the expected results. Although the examples are made for particular topologies, the deployment of different topologies or scenarios could be easily extended by the user as detailed in [4]. Future work will be to simulate RLNC with other technologies, such as Long Term Evolution Advanced (LTE-A) within ns-3.

7. ACKNOWLEDGMENTS

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Paper C.

Paper D

On Transmission Policies in Multihop Device-to-Device Communications with Network Coded Cooperation

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Frank H.P. Fitzek.

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On Transmission Policies in Multihop Device-to-Device Communications with Network Coded Cooperation

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Abstract—Due to the expected amount of interconnected devices in the near future, a frequent communication setting will be the case where the end user is connected to the network through short range communication protocols to other mobile users. Therefore, there is an interest in introducing new mechanisms that provide reliable content distribution in these scenarios. Thus, in this work, we present ideal network coded transmission policies to reduce the number of transmissions in simple multihop networks. We propose two recoding schemes with a collision avoidance mechanism to reduce the number of transmission required to convey a batch of packets from a source to a destination through several non-interconnected relays. Our findings indicate benefits that when employing relays with a recoding scheme and different ideal medium access probabilities, reductions of at least 50% in the total number of transmissions might be attained.

Keywords—Cooperation, network coding, multihop, device-to-device

I. INTRODUCTION

In the following years, an exponential growth in data consumption for new services using telecommunication technologies is expected for future communication systems [1]. A standard assumption in former networks was that a single hop was sufficient to reach an end-user. However, due to this growth in the expected amount of connected devices and services, an end-user might not have connectivity directly from the source of information, but instead through other devices in the network that could aid in conveying information to it. Then, short range based mechanisms that can help to relay data in future network infrastructures have gathered significant interest from both academia and industry [2]–[4].

Thus, there is a major interest in finding decentralized schemes that extend connectivity and coverage in cellular systems while still providing high data rate and reliability to the end user. To achieve this, current alternatives are Device-to-Device (D2D) [5] or WiFi. For this purpose, multihop topologies with D2D communications might be formed to *cooperate* in conveying information to a receiver out of each of the cellular network [6], [7]. In this type of networks, different paths without inter-communication might be formed to reach the end receiver. These paths benefit from spatial diversity to forward the intended data to the final receiver since a loss in a path might be recovered from the correct reception in another. Hence, cooperative techniques result in increased reliability, coverage extension and throughput to end receivers. This potential has resulted in the inclusion of D2D commu-

nications in the 3rd Generation Partnership Project (3GPP) standardization efforts. To recover from packet erasures in the wireless medium, typically rateless codes are employed as a Forward Error Correction (FEC) technique. Nevertheless, although they provide benefits for single hop scenarios, they can not be deployed for cooperative communications without affecting their performance or decoding the data for each hop. Thus, rateless schemes seem an unsuitable coding choice against erasures in cooperative networks.

In this context, Network Coding (NC) [8], and particularly Random Linear Network Coding (RLNC) [9], provides not only an effective, faster and more efficient approach to relay data in multihop networks, but it simplifies the cooperation process since: (i) the information is not simply replicated, but distributed in a useful representation in the network and (ii) the final receiver only needs to get a number of linear combinations from any of the middle devices. This intuition has been exploited in previous works ranging from analysis to optimal policies and practical mechanisms, e.g., [10]–[14]. However, previous work has focused mostly in: topologies where all the cooperating devices inter-communicate with each other to coordinate the information, other scenarios like multicast or cooperation with fully connectivity in small clusters.

Thus, in this work, we present two simple decentralized transmission policies to reduce the total mean number of transmissions required to decode a batch of packets in a two-hop single source, single destination topology with various relays. To avoid collisions from the relays to the destination, we consider a collision avoidance mechanism at the Medium Access Control (MAC) layer that permits to allocate simultaneous transmissions from different nodes. Under this mechanism, we review the impact of a variable relay medium access probability in the number of transmissions to search for medium access probabilities that helps to minimize this metric in order to reduce the redundancy sent in this network. We present a set of ns-3 [15] simulations showing that at least a 30% reduction in the total transmissions, is possible for only enabling recoding at the relays. We also find that for our giving scenarios, an ideal medium access probability permits to reduce even more total packet transmissions. The paper is organized as follows: Section II defines the system model in this study. Section III gives a description of the transmission policies considered. Section IV shows ns-3 simulations to evaluate the policies. Final conclusions and future work are proposed in Section V.

II. MODEL

We consider the problem of reliably transmitting a batch of g packets in a time-slotted system from a source S to a destination D , through R_1, \dots, R_N relays in a 2-hop network as shown in Fig. 1. Each packet has a length of B bits. We model the channel between transmitter $X \in [S, R_i]$ and receiver $Y \in [R_i, D]$ as a packet erasure channel, e.g. packets are sent from X to Y might be erased (lost) with an erasure probability of $\epsilon_{X \rightarrow Y}$. We consider there is not any inter-relay connectivity nor between the source and the destination, thus $\epsilon_{R_i \rightarrow R_j} = 1, \forall i, j \in [1, N]$ and $\epsilon_{S \rightarrow D} = 1$. We consider independent heterogeneous packet erasure rates for each of the connectivity links from the source to the relays, $\epsilon_{S \rightarrow R_i}, i \in [1, N]$ and from the relays to the destinations, $\epsilon_{R_i \rightarrow D}, i \in [1, N]$. Hence, the packet reception distribution of receiver Y from transmitter X is *Bernoulli*($1 - \epsilon_{X \rightarrow Y}$) and is independent from all others.

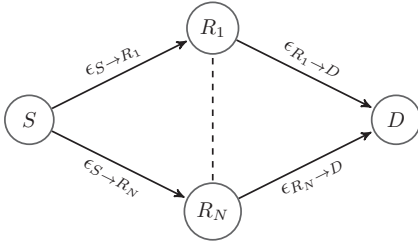


Fig. 1: 2-hop topology of a source (S), N relays (R_1, \dots, R_N) and a destination (D) with a packet erasure rate in each respective link.

Transmissions are performed through two hops. In the first hop, packets are transmitted from the source to the relays in a broadcast with RLNC fashion. The sender stops once each of the relays has g linearly independent (l.i.) coded packets. Through our study, we may refer to a l.i. coded packet as a degree of freedom. A newly received coded packet (or degree of freedom) will be called an innovative packet. Regarding the stopping condition, we may consider other stopping conditions to reduce the sender transmissions, but we consider this one since it is an upper bound for the transmissions in the first hop. Nevertheless, this condition permits to decode the data at the relays with inter-communication, if the content is also of their interest. For the second hop, the relays cooperate as a group to convey the information using either one of two possible recoding schemes, (i) recoding with RLNC or (ii) uncoded random forwarding which both will be detailed in Section III.

For any of these recoding schemes, it does not make sense for all the relays to transmit at the same time since there will be collisions at the receiver. Instead, each relay transmits with probability $p_i, i \in [1, N]$ only if it receives a packet from the sender in a given time slot. For simplicity, we consider $p_i = p, \forall i$. If two or more relays happen to transmit at the same time, we assume that a MAC layer mechanism allocates sequential non-colliding smaller time slots in a local network for the requesting relays. Therefore, in this case, we count the transmissions of the colliding relays as correctly received, regardless if the packets are innovative or not.

To take advantage of the information in the relays and

not await for all to have the batch, once a packet is received from the source by the relays, they attempt to access the local medium with their respective probabilities. If several access the medium, they are scheduled by the MAC and make their transmissions. Thus, the destination benefits from receiving various packets in a single transmission. Finally, we assume that an ideal instantaneous feedback channel exists for any transmitter to know when its intended receivers are able to decode the data for stop sending packets.

III. TRANSMISSION POLICIES

In this Section, we give a description of the transmission policies employed to send the data. First, we provide a short description for RLNC as a coding scheme considered to broadcast the data from the source to the receivers. Later, we describe the recoding schemes employed at the relays and the MAC mechanism to avoid collisions of simultaneous transmitting relays.

A. Source to Relays: Broadcast with RLNC

In this type of network coding, the original data $P_j, j \in [1, g]$, each of B bits, is used to create coded packets. In the following subsections, we describe the basic functionalities of RLNC [9], namely encoding and recoding.

1) *Encoding*: With RLNC, each coded packet is a random linear combination of the original set of g packets. Each original packet is considered as a concatenation of elements from a Galois Field (GF) of a given size q , which we denote $GF(q)$. To create a coded packet, a coding coefficient $v_{i,j}$, is chosen at random from $GF(q)$ for every packet P_j and multiplied and added following the respective GF arithmetics. In this way, a coded packet is:

$$C_i = \bigoplus_{j=1}^g v_{i,j} \otimes P_j, \forall i \in [1, g] \quad (1)$$

To indicate which packets were used to generate a coded packet, one form is to append its coding coefficients. In this case, the overhead included for $C_i, \forall i \in [1, g]$ by the coding coefficients is given by:

$$|v_i| = \sum_{j=1}^g |v_{i,j}| = g \times \lceil \log_2(q) \rceil \text{ [bits]} \quad (2)$$

2) *Decoding*: To perform decoding, at each relay we define $\mathbf{C} = [C_1 \dots C_g]^T$ and $\mathbf{P} = [P_1 \dots P_g]^T$. Then, decoding reduces to solve the linear system $\mathbf{C} = \mathbf{V} \cdot \mathbf{P}$ using Gaussian elimination [16]. Here, the coding matrix \mathbf{V} contains any set of g linearly independent packets C_i as rows as follows:

$$\mathbf{V} = \begin{bmatrix} v_{1,1} \\ \vdots \\ v_{g,1} \end{bmatrix} = \begin{bmatrix} v_{1,1} & \dots & v_{1,g} \\ \vdots & \ddots & \vdots \\ v_{g,1} & \dots & v_{g,g} \end{bmatrix} \quad (3)$$

The decoder begins to compute and remove the contributions from each of the pivot elements, e.g. leftmost elements in the main diagonal of (3), to reduce \mathbf{V} to reduced echelon form. In this way, it is possible to recover the original set of packets. When a packet successfully arrives at a receiver, it checks if

the packet is l.i. from all its previous. If not, it discards it. In case of being l.i., the receivers adds it to its coding matrix as mentioned before. This repeats until all receivers have collected their required combinations. An Acknowledgment (ACK) is sent through the feedback channel from the last relay after it gets its final combination and the source stops sending packets.

B. Relays to Destination I: Recoding Schemes

If a packet arrives at a relay, it will proceed to send the data to the destination according to a given recoding scheme. In our study, we consider two recoding schemes which we describe subsequently.

1) *RLNC Recoding Scheme*: Network coding allows intermediate nodes in a network to recombine (or recode) packets obtained from their sources whether they are coded or not. Thus, we define a recoded packet as R_i and its corresponding encoding vector as w_i with coding coefficients $[w_{i,1} \dots w_{i,g}]$, as follows:

$$R_i = \bigoplus_{j=1}^g w_{i,j} \otimes C_j, \forall i \in [1, g] \quad (4)$$

In (4), $w_{i,j}$ is the coding coefficient that multiplies C_j , uniformly and randomly chosen from $GF(q)$. Notice that C_j is a packet received previously which might be coded already. However, this does not affect the original encoding since a recoded packet is again a (new) linear combination of the previous ones. Any destination that collects $R_i, i \in [1, g]$ linearly independent coded packets from all the relays, appended with their respective w_i similarly as in (2), will be able to decode the data as mentioned before. In this scheme, a relay sends recoded packet only if the rank of its coding matrix is greater than zero. Otherwise, it will always generate linearly dependent packets which may introduce overhead in the network. Still, some redundant packets might be sent given that, particularly at the beginning of the transmission process, a relay might have few coded packets to combine. However, as more l.i. coded packets are received, this redundancy tends to diminish.

2) *Random Forwarding Scheme*: For this case, all the packets received by a relay before acknowledging decoding are stored by it. Then, once a packet arrives at a relay, it simply forwards uniformly at random one of the currently stored packets. Although storage resource consuming, forwarding any of the previous packets nulls the possibility that any pair of relay always send two inter-dependent coded packets. Still, in this scheme, a relay is constrained to send distinguishable packets, reducing the total amount combinations that could possibly be sent. Any destination that collects g l.i. coded packets from all the relays will be able to decode the data. Same as before, a relay tries to forward a previously received packet if its rank is greater than zero.

C. Relays to Destination II: Collision Avoidance Mechanism

Once a packet is generated with any of the previous recoding schemes, a relay senses the wireless local medium and access with probability p . If two or more relaying devices coincide in a packet transmission, we assume (without loss of generality) a MAC mechanism that allocates non-colliding

time slots for each coinciding relay in order to avoid collisions. The detection time of a possible collision is considered to be ideal. Thus, coinciding relay nodes do not abort the current transmission and incur in retransmissions. Hence, a single transmission is accounted for each of the coinciding nodes.

IV. SIMULATION RESULTS

To analyze the performance of our proposed transmission policies, we execute a set of ns-3 [15] simulations to observe the effect of the recoding scheme, code parameters and number of relays under a given combination of packet erasure rates in the links.

We consider the number of transmissions as a metric since other metrics such as the energy or throughput, which affect performance of cellular and wireless networks, depend directly on the number of transmissions for data decoding. We evaluate this metric at the source, the relays and the total amount of transmissions required to get the content at the destination. For evaluation purposes, we make this computations under homogeneous source-relays and relays-destination packet erasure probabilities for all the relays, e.g. $\epsilon_{S \rightarrow R_i} = \epsilon_{S \rightarrow R} \forall i \in [1, N]$ and $\epsilon_{R_i \rightarrow D} = \epsilon_{R \rightarrow D} \forall i \in [1, N]$.

To accomplish this, we employ the Kodo C++11 network coding library [17] with ns-3 through a project stored in a Git repository [18] that contains a set of examples using a set of Kodo C++ bindings with ns-3. A descriptive tutorial for this project can be found in [19]. From the repository, we run the `kodo-wired-broadcast` example and get the number of transmissions required to decode the data in 10^3 runs. To get independent runs, the pseudo-random number generator is set to use the default seed and the `RngRun` parameter is set equal to the run number in the `ns3::RngSeedManager` class. With the previous data, we compute the distribution for the number of transmissions in each of the nodes and later extract the mean of it.

For the simulations, we use the following parameters: $N = [1, 2, 3]$, $g = [8, 16, 32, 64]$, $q = [2, 2^8]$, $\epsilon_{S \rightarrow R} = [0.1, 0.3]$, $\epsilon_{R \rightarrow D} = [0.1, 0.3]$, $p = [0.01, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]$ for the medium access probability and the recoding schemes considered in Section III.

A. The effect of the Number of Relays (N)

Fig. 2 shows the effects of the number of users in the total amount of transmissions from both the sender and the relays. We show it for the case of the random forwarding scheme, packet erasure probabilities $\epsilon_{S \rightarrow R} = 0.3$, $\epsilon_{R \rightarrow D} = 0.1$ and code parameters $g = 32$, $q = 2^8$. In this scheme, we observe that for more than one relay, there is a reduction in the total amount of transmissions required for decoding. Including more relays permits to have more sources of possible l.i. coded packets for the destination. However, in this case, always increasing the number of relays is not the optimal strategy because they may share various degrees of freedom. The ideal number of relays depends on the medium access probability. For a low access probability in the random forwarding scheme, the relays transmission attempts are reduced helping them collect different sets of degrees of freedom. For a high medium

access probability, more transmissions at the relays of non-innovative packets tend to occur, given that they forward similar set of packets at the beginning. Hence, fewer relays are useful in this scenario. Notice that in this case, new coded packets are only introduced by the source.

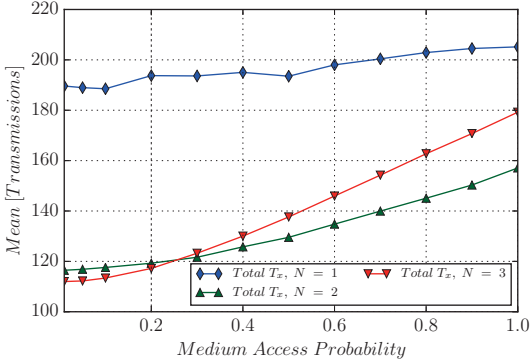


Fig. 2: Mean total number of transmissions, $Total T_x$, for decoding at the destination with a different amount of relays using a Random Forwarding Scheme. Scenario: $\epsilon_{S \rightarrow R} = 0.3$, $\epsilon_{R \rightarrow D} = 0.1$. Parameters: $g = 32$, $q = 2^8$.

B. The effect of the Recoding Scheme and Field Size (q)

Fig. 3 shows the effects in the total number of transmissions by using a RLNC Recoding Scheme with different field sizes. We show it for the case of $g = 32$ packets, packet erasure probabilities $\epsilon_{S \rightarrow R} = 0.3$, $\epsilon_{R \rightarrow D} = 0.1$ and field sizes $q = 2$, 2^8 . Allowing the relays to recode packets from their received degrees of freedom, reduces the total amount of transmissions for decoding by at least 30%, when comparing the results for $GF(2^8)$ in Fig. 2 and Fig. 3. The inherent recoding capability of RLNC makes each recoded packet indistinguishable from others, removing the restriction of receiving specific packets as in the forwarding scheme. Also, in Fig. 3, it can be observed the effect of the field size. Here, using a high field provides the advantage of requiring less transmissions than using a lower one, regardless of the number of relays. The reason is that, in the high field case, innovative packets are generated with very high probability.

We also observe there is an optimal medium access probability that minimizes the total number of transmissions for a given number of relays. From Fig. 3, a low medium access probability increases the number of transmissions required in the first hop as we consider more relays. The lower the access probability, the higher amount of time slots that a relay needs to wait for attempting a transmission and the higher amount of transmissions that the source makes since it stops transmitting once all the relays have all the degrees of freedom. For a high access probability, the relays access more frequently the medium to transmit data, reducing the amount of transmissions from the source. However, if the access probability is too high, various redundant transmissions are made near the end.

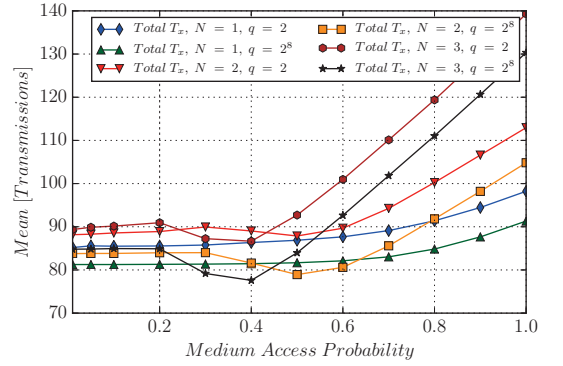


Fig. 3: Mean total number of transmissions, $Total T_x$, for decoding at the destination with different field sizes using a RLNC Recoding Scheme. Scenario: $\epsilon_{S \rightarrow R} = 0.3$, $\epsilon_{R \rightarrow D} = 0.1$. Parameters: $g = 32$, $q = 2$, 2^8 .

C. Source and Relay Transmissions, Generation Size Effect (g)

Fig. 4 and Fig. 5 show the number of sender, relay and total transmissions employing a RLNC Recoding Scheme with two generation sizes. Fig. 4 shows the case of two relays, while Fig. 5 the case of three relays.

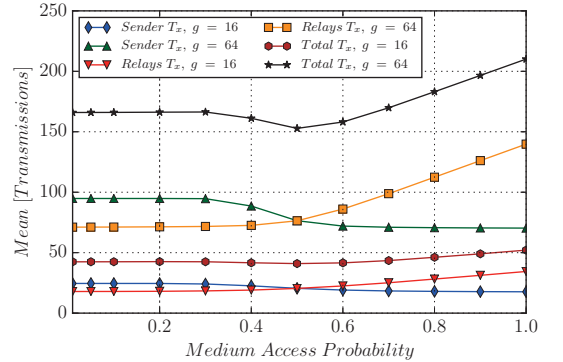


Fig. 4: Mean Sender (Source), Relays and Total number of transmissions, $Sender T_x$, $Relays T_x$, $Total T_x$ for 2 relays with different generation sizes using a RLNC Recoding Scheme. Scenario: $\epsilon_{S \rightarrow R} = 0.3$, $\epsilon_{R \rightarrow D} = 0.1$. Parameters: $N = 2$, $q = 2^8$.

Using a higher generation size simply requires more transmissions given that more degrees of freedom are needed to be sent to the destination. It occurs independently of the number of relays to aid the source since it only varies with the generation size. By separating the sender and relays transmissions, we observe how the optimal medium access probability arises and where does it occur. As mentioned previously with Fig. 3, a low access probability increases the number of transmissions from the sender whereas a high access probability does the proper for the relays. We again observe these effects in both Fig. 4 and Fig. 5. Moreover, the total amount of transmissions is minimal particularly when the medium access probability

approaches $p = 1/N$ approximately, e.g. a uniform medium access probability in all of the cases.

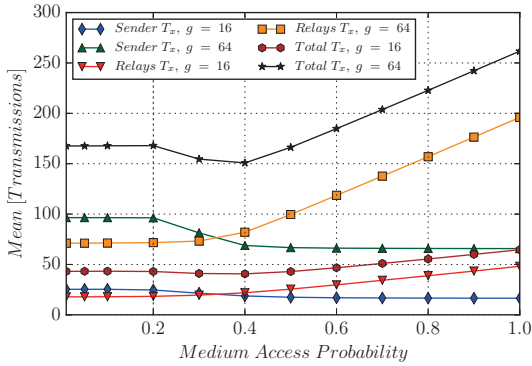


Fig. 5: Mean Sender (Source), Relays and Total number of transmissions f, Sender T_x , Relays T_x , Total T_x for 3 relays with a different generation sizes using a RLNC Recoding Scheme. Scenario: $\epsilon_{S \rightarrow R} = 0.3$, $\epsilon_{R \rightarrow D} = 0.1$. Parameters: $N = 3$, $q = 2^8$

V. CONCLUSIONS

In this work, we propose different transmission policies to reduce the mean number of transmissions in network coded cooperative systems, since this a key metric that controls other relevant ones such as the energy consumption or the throughput. Through extensive system simulations, we could observe the benefits of a RLNC recoding scheme with a MAC collision avoidance mechanism to exploit the benefit of spatial diversity with a set of relays in multihop communications, observing a reduction in the number of transmission for various medium access transmission probabilities. Future work in this area should focus on evaluating ideal policies for minimum completing time as evaluated in [20] and [10] for similar topologies.

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